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Valorisation of industrial brewer's spent grains as a carbon-rich resource for sustainable food and feed systems

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ABSTRACT

Brewer's spent grain (BSG) is the largest by-product of the brewing industry, and it is produced in substantial quantities across the world. However, the by-product is not being utilised to its full potential despite its high carbon content. This article aims to present a critical review of the valorisation of industrial brewer's spent grains as a carbon-rich by-product for the development of sustainable food and feed systems in the context of the bioeconomy and low-carbon food systems. This article aims to present a critical review of the generation, physicochemical properties, and chemical composition of brewer's spent grains as a carbon-rich by-product of the brewing industry. The carbon-rich nature of the by-product makes it suitable for various valorisation options such as functional food, animal feed, bioenergy, bio-based chemicals, biomaterials, and carbon-based materials such as activated carbon and biochar. The review also assesses the technologies for industrial processing and fractionation of the material necessary to unlock the potential of the BSG. These include drying, milling, pre-treatment, enzymatic hydrolysis, and fermentation. Environmental and sustainability assessment, such as the carbon footprint reduction potential of the material, is also discussed in the context of the overall impact of the material. Finally, the potential challenges and future research directions for the implementation of the biorefinery system to unlock the potential of the carbon in the material are also discussed.

1. Introduction

The global brewing industry is a large agro-industrial sector with considerable economic and material throughput, where enormous quantities of by-products are produced along with beer. The global production of beer was around 1.94 billion hectoliters in 2018. This indicates the enormous scale of raw materials processed and by-products produced [1]. Among these by-products, brewer spent grains (BSG) are the largest by-product of brewing, with almost 85% of total brewing by-products [2]. BSG is produced during mashing and wort filtration. It is composed of malted barley with an insoluble fraction. It contains husks and endosperm. The quantity of BSG produced per hectoliter of beer is between 20 and 22 kg. This means around 39 million tonnes of BSG are produced globally [3]. This enormous scale of BSG indicates its environmental impact and potential.

From a compositional point of view, BSG is a carbon-rich material composed of a complex mixture of cellulose (25%), hemicellulose (43%), lignin (28%), and proteins present between 20% and 30% on a dry matter basis [1], [4]. Mussatto et al. [2] also indicated that the composition of BSG is composed of 17% cellulose, 28% non-cellulosic polysaccharides, and 28% lignin, along with considerable protein and fibre content, making it an attractive feedstock for nutritional and biotechnological purposes. In a similar vein, Nyhan et al. [5] indicated the generation of BSG to be around 20 kg/hl of beer produced and the high moisture content (75–80%), making the material more susceptible to microbial spoilage. This gives rise to the paradoxical character of the material: the more it is produced, the less it is utilised. Presently, the most common practice of BSG utilisation is its low-value uses, such as animal feed, which constitutes approximately 70% of its global utilisation, while smaller portions are utilised for biogas or landfilled.

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Although this practice presents a partial valorisation of BSG, it does not represent the full utilisation of its economic and functional potential, especially considering its rich composition of dietary fibres, proteins, phenolic compounds, and micronutrients [3]. The continued dominance of such low-value utilisation of BSG results from systemic inefficiencies in the management of agro-industrial wastes. Additionally, the high moisture content of fresh BSG complicates its transport and carbon footprint.

Against this background, the idea of carbon waste valorisation has emerged as a core component of a bio-based economy. Whereas BSG was traditionally considered a waste product, the new paradigms recognise BSG as a renewable source of carbon that can be used as a precursor for the production of high-value food ingredients, functional animal feed, and other bio-based products. This approach assumes particular importance in the context of global sustainable development challenges, which include issues of resource depletion, global warming, and food security, among others. The lignocellulosic and protein content of BSG make it a potential source for the production of a variety of products, which include dietary fiber concentrates, protein-rich ingredients, bioactive compounds, and fermented ingredients, among others [5]. Significantly, these valorisation opportunities for BSG are also in line with the principles of the circular economy, which emphasize resource efficiency, waste reduction, and the closing of loops in food production systems. Despite increased research interest in valorising BSG, this process remains fragmented and faces several technical and systemic challenges, including compositional differences arising from variations in raw materials and brewing methods, as well as technological limitations in valorising BSG. Moreover, the utilisation of BSG is hampered by regulatory, sensory, and consumer acceptance issues. Most importantly, the majority of studies have focused on specific aspects rather than adopting a holistic view that encompasses all aspects of food, feed, and biorefinery.

Therefore, this review aims to provide a comprehensive and critical review of the valorisation of industrial brewers' spent grains as a carbon-rich material for sustainable food and feed systems. It will include an assessment of the generation, composition, and utilisation of BSG, as well as the development of novel technologies and applications to convert BSG into valuable products. This review will help reposition BSG from a waste material to a valuable resource for sustainable food systems.

2. Industrial generation and characteristics of brewer's spent grains

Brewer's spent grain (BSG) is the largest solid by-product of the brewing process, with an estimated 20–22 kg of BSG being produced per hectolitre of beer. BSG contributes to almost 85% of the total residues from the brewing process. Beer production exceeds 1.9 billion hectolitres annually worldwide, as presented in Table 1 [2]. BSG production is thus in the range of tens of millions of tonnes annually. BSG has high moisture content (75–80%) when fresh, making it highly perishable and leading to problems of storage and utilization. Lignocellulosic content rich in cellulose, hemicellulose (arabinoxylans), and lignin provides opportunities for biofuel production, bio-based materials, and functional dietary fibres. Rigidity of the cell walls necessitates pretreatment for effective processing [6,7]. Protein content (12.5–35.4%), dietary fibres (up to 70%), lipids, ash content, and phenolics increase the potential of BSG for animal feed, functional food components, nutraceuticals, and energy production [8,9]. However, the variation in BSG composition depending on barley variety and brewing conditions poses

Table 1
Key Characteristics of Brewer's Spent Grain (BSG) and Their Implications for Valorisation.

Aspect	Key findings from the literature	Scientific/Industrial interpretation	Analysis	Implication for valorisation
Global generation scale	Approximately 20–22 kg of brewer's spent grain (BSG) is produced per hectolitre of beer, accounting for about 85% of total brewing by-products [2]	Indicates BSG as the dominant solid residue from brewing processes	High-volume generation creates a continuous supply, but also logistical burdens in handling and disposal	Supports industrial-scale valorisation systems such as biorefineries and circular food systems
Annual production volume	An estimated tens of millions of tonnes globally, based on beer production exceeding 1.9 billion hectolitres per year [10]	Reflects BSG as one of the largest agro-industrial lignocellulosic wastes	Underutilization at this scale reflects inefficiencies in agro-industrial resource recovery	Opportunity for global carbon valorisation and waste-to-resource conversion
Moisture content	Typically, 75–80% moisture in fresh BSG; high moisture accelerates microbial spoilage	High water content promotes rapid microbial growth and degradation [6,7]	Major bottleneck for storage, transport, and long-term utilisation	Necessitates drying, stabilisation, or immediate processing technologies [11]
Lignocellulosic composition	Cellulose (8.9–38.8%), hemicellulose (19.2–26%), lignin (12–27.8%) [12,13]	Confirms BSG as a lignocellulosic biomass rich in structural carbohydrates [14]	Structural rigidity limits enzymatic accessibility without pretreatment	Enables conversion into biofuels, biomaterials, and dietary fibre ingredients
Detailed structural composition	Mussatto et al. [2] reported approximately 17% cellulose, 28% hemicellulose (arabinoxylans), and 28% lignin	High arabinoxylan content enhances functional properties such as water retention and viscosity	Variability in composition affects process standardization and product consistency	Targeted fractionation can yield high-value compounds such as xylo-oligosaccharides and ferulic acid
Protein content	Typically, 12.5–35.4% on a dry basis [8]	Significant residual protein remains after starch extraction	Protein quality varies depending on the barley source and brewing conditions	Suitable for animal feed, protein enrichment, and fermentation substrates
Dietary fibre content	Up to approximately 70% total dietary fibre (cellulose and hemicellulose) [15]	High insoluble fibre enhances gut health and functional food applications	Poor digestibility without modification limits direct human consumption	Ideal for functional foods, prebiotics, and fibre fortification
Lipid and ash content	Lipids: 3–13.5%; Ash: approximately 3–5% [16,17]	Minor components but relevant for nutritional and thermal properties	Lipid oxidation may affect storage stability	Contributes to energy recovery, such as bioenergy and combustion systems
Phenolic compounds	Approximately 0.7–2% phenolic compounds with antioxidant properties [18]	Presence of bioactive compounds such as ferulic acid	Often underexploited due to a lack of efficient extraction technologies	Potential for nutraceuticals and antioxidant-rich food ingredients
Variability factors	Composition influenced by barley variety, malting, mashing, and brewing conditions [15]	Industrial variability leads to inconsistent physicochemical properties	Major challenge for process optimization and product standardization	Requires adaptive processing technologies and quality control systems
Current industrial utilization	Predominantly used as low-cost animal feed in many regions [19,20]	Reflects a low-value recovery pathway despite high compositional richness [21]	Economic underutilisation of a carbon-rich biomass	Strong case for upgrading to high-value food, feed, and bioproduct applications

a challenge for the standardization of the process and consistency of the product. BSG is mainly used as a cheap animal feed, but its potential for Valorisation into valuable industrial products is untapped.

3. Brewing process and origin of BSG

The production of brewer's spent grains (BSG) is closely tied to the fundamental steps in brewing, particularly mashing and lautering, where raw materials are modified and separated. Brewing starts with the malting of cereals, primarily barley, which are then milled and mixed with water at high temperatures during the mashing process. During this process, starches are hydrolyzed by enzymes, particularly amylases, into fermentable sugars, while proteins are degraded, particularly into soluble peptides and amino acids. Consequently, 60–70% of the dry mass of the malt is dissolved in the form of a liquid extract called wort, leaving behind an insoluble fraction, which finally gives rise to BSG [19]. The production of BSG can be considered to be at the core of the process of brewing, as BSG results from a selective process in mashing, where soluble components are transferred from the malt, leaving behind the insoluble components, which are primarily barley husk, pericarp, seed coat, and endosperm [22]. After mashing, the mixture then goes through a process called lautering, where physical separation of the liquid from the solid matrix occurs.

The recent findings on brewer's spent grains (BSG) have again emphasized that the origin of brewer's spent grains in the brewing process is not just a passive formation of residues, but rather a product with a high degree of structure and biochemical complexity that has a high degree of functional potential. Brewer's spent grains are known to have originated during the mashing and lautering process of brewing as the insoluble fraction of the barley grains after the extraction of the wort; however, recent research has indicated that brewer's spent grains have a high degree of biochemical complexity due to the selective action of the enzymes during the mashing process. Brewer's spent grains contain high levels of cellulose, hemicellulose, and protein that remain underutilised during the mashing process. Nattha Lojananan et al. [23] have indicated that brewer's spent grains, which have originated from the partially hydrolysed brewer's spent grains, have a high degree of potential for the production of lignocellulolytic enzymes with Trichoderma sp., where cellulase activity was observed to be 35.84 U/g-BSG with a high degree of xylanase activity up to 599.61 U/g-BSG.

Likewise, the protein fraction retained in BSG due to incomplete solubilisation during mashing was found to be rich in. This indicates that the structural carbohydrates present during brewing are not inert but highly reactive under appropriate biological conditions. However, this study demonstrated that these enzymes could saccharify pretreated BSG and produce up to 59.3 g/L of lactic acid, thereby establishing a link between the source of BSG in brewing and its biochemical convertibility and potential. Jiao Zhang et al. [24] demonstrated that during solid-state fermentation of BSG, the efficiency of protein extraction was increased to 0.678 μg/μL, almost doubling the efficiency of protein

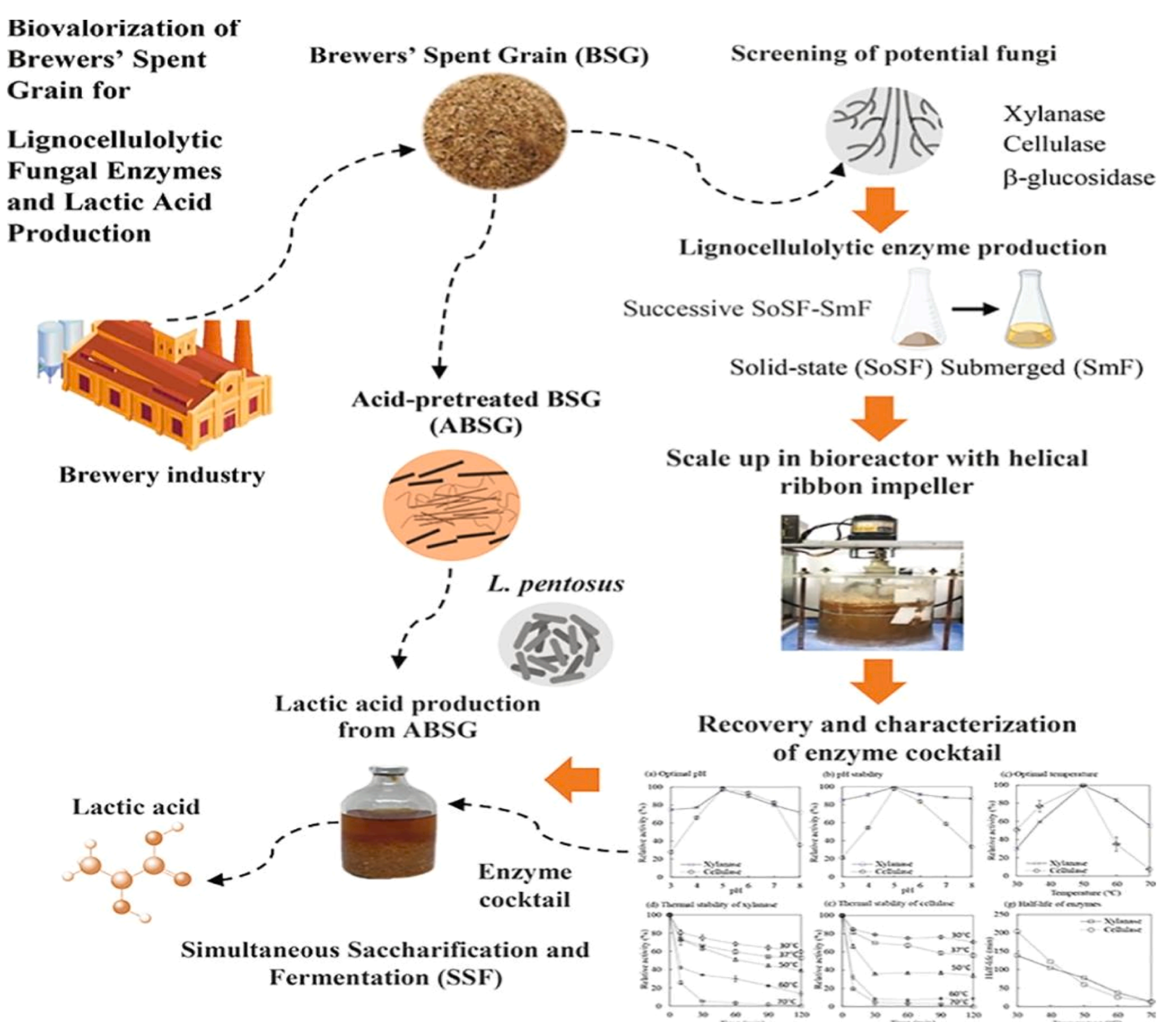

Fig. 1. Schematic illustration of the biovalorisation of brewer's spent grain (BSG) through screening of lignocellulolytic fungi and production of enzymes (xylanase, cellulase, and β-glucosidase) using solid-state fermentation (SSF), submerged fermentation (SmF), and successive SSF–SmF processes (Lojananan et al. [23]).

extraction compared to untreated BSG. This result reinforces the notion that the brewing process results in modified protein structures that are recoverable and can be upgraded through biotechnological interventions. In a related vein, Joncer Naibaho et al. [25] also found that enzymatic treatment of BSG protein significantly enhances antioxidant activity and functional properties, suggesting that the protein structures left behind during the brewing process are recoverable and can be upgraded. Apart from biochemical transformations, the structural integrity of BSG from the brewing process also offers opportunities for fractionation of BSG into advanced materials for biotechnological applications. In a recent study, Qazanfarzadeh et al. [26] found that BSG can be fractionated into protein–lignin, hemicellulose, and nanocellulose, which can be recombined as functional materials with enhanced mechanical and antimicrobial properties. This suggests that the source of BSG from the brewing process itself defines its suitability for biorefinery applications. Fig. 1 demonstrates the overall biovalorisation pathway for brewer's spent grain (BSG), showing the screening of lignocellulolytic fungi and the production of lignocellulolytic enzymes via solid-state and submerged fermentation processes to generate value-added bioproducts.

The solid matter retained and accumulated in the lauter tun is called brewer's spent grains. Mussatto et al. [2] stated that the composition of BSG is the result of the insoluble matter left after enzymatic hydrolysis and the extraction of the wort. This indicates that BSG is not a primary waste but a by-product arising from the biochemical processes of the brewing process. In terms of the quantitative relationship between the brewing process and the production of BSG, it has been found by Birsan et al. [3] that 21–22 kg of BSG is produced per hectolitre of beer. This indicates that a large proportion of the raw material is not converted into the final beer. In addition, it has been found that only 31% of the initial raw material weight is converted into the final beer [10]. This indicates that the brewing process is a biochemical process in which the lignocellulosic biomass is resistant to enzymatic hydrolysis. Critically, the origin and nature of BSG are greatly influenced by brewing parameters such as the type of grains used, mashing conditions, and the temperature regime during brewing [19]. Specifically, the addition of adjunct grains such as wheat, maize, or rice alters the structure and chemical composition of the resulting BSG, making it heterogeneous. Moreover, changes in mashing parameters, such as temperature and time, affect the solubilization of starches and protein components, thereby influencing the composition of the spent grains [27]. BSG should not be regarded simply as a by-product but rather as a residue of biochemical processing. This means that BSG is actually produced by selective extraction mechanisms inherent in brewing. This understanding of BSG means that its origin at the process level is critical for designing valorisation strategies compatible with its structural and compositional characteristics [28]; [29].

4. Global industrial production volumes

Global industrial production of brewer's spent grains (BSG) is directly proportional to the scale of beer production, thereby making it one of the largest agro-industrial residues in the world. The scale of beer production, i.e., more than 1.8–1.9 billion hectolitres per annum, makes BSG production remarkably consistent and reliable globally. Using industrial conversion factors, the production of BSG is about 20 kg of wet BSG per 100 L of beer, thereby yielding about 36–39 million tonnes of BSG per annum globally [30]. In terms of scale, BSG production varies by region, with the Americas, Asia, and Europe the major contributors globally. Using the data on the global scale of production, the production of BSG in America, including both North and South America, is more than 12 million tonnes, followed by Asia (11 million tonnes) and Europe (10 million tonnes), whereas Africa and Oceania produce smaller quantities of BSG [31]. More importantly, the industrial scale of BSG generation is not limited to the global economy but is also evident at the national and facility levels. In the United States, one of the largest beer manufacturers in the world, the annual generation of BSG is estimated at around 4.5 million tonnes, while individual large-scale breweries can generate around 0.2 million tonnes of BSG per annum [30]. In the European Union, the annual production of BSG has been estimated at around 3.4 million tonnes, further confirming the large-scale generation of this residue [32].

At the regional level, production volume follows the global pattern of beer consumption, with the Americas, Europe, and Asia contributing the highest production volumes. The importance of BSG production, however, goes beyond the volume of production to the recognition of this by-product as a strategic secondary raw material in the emerging circular bio-economy scheme. Anđela Zeko-Pivač et al. [31] noted that the large-scale and continuous production of BSG in the brewing industry makes it a key material for the development of future biorefineries, especially in regions such as Central and Eastern Europe, where the biomass valorisation market is growing. More importantly, the large-scale production of BSG is also characterised by physicochemical properties. In a recent study, Głowacki et al. [32] reported that wet BSG typically contains 77–80% moisture. The authors also reported a calorific value of 15.6–15.9 MJ/kg for dry BSG and a reduction of approximately 1.4–2.0 MJ/kg associated with the reported moisture content. The high moisture content, therefore, substantially reduces the energy density of fresh BSG and must be considered when assessing its potential for energy recovery. These reported values should be interpreted according to the measurement basis and methodology used in the original study and should not be directly compared without distinguishing between higher heating value (HHV) and lower heating value (LHV). Also, the large-scale production of BSG underscores its usability and applicability in industrial materials. Also, Rachwał et al. [33] noted that BSG can be added up to 30 wt% to bio-composites while maintaining thermal stability and improving biodegradability. Most importantly, the high-scale and constant generation of this residue poses a paradox for breweries around the world. Although large-scale generation of this residue ensures the availability of raw materials for producing various products, it also poses logistical, environmental, and economic challenges for breweries [33]. Thus, the global production statistics not only provide an idea of the high-scale generation challenge but also emphasise the need for a shift from existing valorisation practices to an integrated system for valorising this high-scale-generated biomass.

5. Physical structure and moisture content

Brewer's spent grains (BSG) are a significant waste product from the lautering step of brewing, in which insoluble barley parts are removed from the wort. The resulting lignocellulosic material is characterised by a highly porous and fibrous morphology. From a physical perspective, brewer's spent grains are composed of barley husk, pericarp, and endosperm, which are present in a random matrix. The fibrous nature of brewer's spent grains is characterised by a high surface area and water-holding capacity, which is greater than 20 g/g dry matter. This is significant, as it impacts the handling and valorisation of brewers' spent grains [34]. The heterogeneous nature of brewer's spent grains, consisting of both fine and coarse particles, also impacts density, ranging from 384 to 495 mg/cm^3, depending on the degree of compaction during discharge [34]. On the other hand, the moisture content is the key physical characteristic of freshly produced BSG. In general, the moisture content of freshly produced BSG is between 75% and 85%, with an average of around 79–80% [35]. Moreover, recent research indicated that around 100–130 kg of BSG with a moisture content of 70–80% is produced for every 100 kg of malt grains processed [36]. This high moisture content is closely related to the porous lignocellulosic composition of the BSG. However, the moisture content can change drastically upon drying the BSG to less than 5%, as indicated by recent research by Santos et al. [38], which reported a moisture content of around 5.05% after thermal treatment. Similarly, the moisture content of dry BSG samples is around 2–5%, indicating successful removal of water from the lignocellulosic matrix. This drastic change from high to low moisture content can significantly affect the physicochemical properties of BSG. In summary, the interplay between the fibrous composition and the high moisture content is the key factor for the stability and utilisation of the BSG [37].

6. Variability due to raw materials and brewing conditions

Fundamentally, the raw material heterogeneity and the brewing process conditions are the two main factors affecting the variability of brewer's spent grains (BSG), which are responsible for the considerable physicochemical diversity observed among brewing systems. In the raw material aspect, the diversity observed among barley varieties, harvest conditions, and composition is a key factor affecting the physicochemical properties of the brewer's spent grains. As highlighted in Table 2, the diversity observed in the husk thickness and lignocellulosic composition is mainly influenced by the barley genotype and agronomic factors. This diversity is responsible for the considerable variations observed in the fibre and protein content. Santos et al. [38] observed that barley variety, timing of harvest, and adjunct composition significantly influence the composition of the brewer's spent grains. This is mainly attributed to the raw material heterogeneity. Besides the raw material composition, the use of adjunct grains such as maize, rice, and wheat also influences the composition of the brewer's spent grains by affecting the balance between the carbohydrate and lignin content. In recent years, considerable variations have been observed in the composition of the brewer's spent grains, mainly attributed to the use of adjunct grains [39]. Besides this, brewing conditions also play an important role, specifically mashing temperature, enzymatic activity, and lautering efficiency, which influence the extent of starch and protein extraction. Hence, the composition of the residual matter present in the BSG may change depending on the brewing conditions. Naibaho et al. [37] stated that the composition of the BSG produced from eight different breweries showed considerable variations in moisture content, protein content (14.5–30%), fat content (8–34.8%), and water-holding capacity. This further proves the point that the technologies used by different breweries may cause additional variations.

Thus, it can be stated that the BSG is not a constant by-product; rather, it is a variable biomass influenced by both the raw agricultural materials and the brewing technologies.

7. Carbon-rich composition of brewer's spent grains

Brewer's spent grains (BSG) are naturally carbon-rich materials due to their lignocellulosic composition, which comprises a significant proportion of biopolymer materials, i.e., cellulose, hemicellulose, and lignin, which are collectively responsible for the high carbon content in BSG, resulting from the barley husk and cell wall residues left behind after the wort separation process. In general, BSG comprises 20–25% cellulose, 15–35% hemicellulose, and 10–25% lignin, which collectively contribute significantly to the fixed carbon content of BSG [41]. This suggests that a large proportion of BSG consists of carbon-rich polysaccharides, which are important for the production of carbon-based materials. According to a study conducted by Vanreppelen et al. [42] on BSG, the results indicated that BSG comprises 20.8 wt% cellulose, 48.78 wt% hemicellulose, and 11.3 wt% lignin, which are responsible for the high density of carbon content in BSG, making it a suitable source for the production of activated carbon materials. Likewise, Gebreyes et al. [40] found that BSG has a carbon-to-nitrogen ratio of about 13.9, which is considered relatively high for a protein-rich material. However, it is also noteworthy that lignin's aromatic character is advantageous for carbon stability, and the cellulose and hemicellulose components contribute to carbon yield in thermal conversion processes. This carbon model not only characterizes the physicochemical properties of BSG but also highlights its significance in biochar, adsorbent, and energy-related applications

8. Structural carbohydrates (cellulose, hemicellulose, lignin)

Brewer's spent grains (BSG) have a carbon-rich composition, which can be characterized as primarily structural in nature, consisting of components such as cellulose, hemicellulose, and lignin, which are responsible for the rigidity and functional value of BSG [4]. These components are responsible for the majority of the dry mass of BSG, which are collectively known as the backbone of the barley husk matrix, as they are left behind in the process of wort separation from barley malt [43]. The fibrous composition of BSG can be attributed to the presence of plant cell wall components, which are left behind due to resistance towards enzymatic hydrolysis during the mashing process, thereby enriching BSG in terms of structural components [44]. According to Lynch et al. [45], BSG can be characterized as primarily consisting of

Table 2
Variability of brewer's spent grains (BSG) due to raw materials and brewing conditions.

Variability factor	Source of variation	Observed effects on BSG characteristics	Reported data	Effect
Barley cultivar (genetic variation)	Differences in barley genotype and grain composition	Alters the fibre structure, protein, lignin, and silica distribution	Protein ranges from 22 to 30%, carbohydrates 50–60% across samples [37]	Genetic variability introduces baseline heterogeneity, making standardisation of BSG properties difficult for industrial reuse
Harvest timing & agronomic conditions	Climate, soil quality, and maturity at harvest	Influences husk thickness, lignocellulosic rigidity, and nutrient retention	Variability linked to planting time and crop conditions [40]	Seasonal and geographic differences lead to inconsistent structural integrity and processing behavior
Use of adjuncts (e.g., maize, rice, wheat)	Partial substitution of barley in the mash bill	Modifies fiber composition, reduces lignin content, and alters particle morphology	Adjunct selection significantly contributes to compositional diversity [39]	High adjunct use reduces uniformity of BSG, affecting downstream applications such as bio-composites or adsorbents
Malting conditions	Germination time, kilning temperature	Affects enzymatic breakdown and cell wall modification	Variability in arabinoxylan and cellulose fractions reported [15]	Malting intensity controls structural degradation, influencing the porosity and reactivity of BSG
Mashing parameters (temperature, time, water ratio)	Extraction efficiency during wort production	Determines residual starch, protein concentration, and moisture retention	Residual composition reflects the extent of starch removal during mashing [15]	More intensive mashing yields fibre-rich, structurally compact BSG with altered hydration behaviour
Lautering and separation efficiency	Wort separation technique and equipment	Affects particle size distribution and retained liquid	Variations in density and water-holding capacity observed across breweries [37]	Inefficient separation increases moisture heterogeneity and impacts storage stability
Brewery-specific processing technology	Industrial vs craft brewing systems	Leads to batch-to-batch variability in composition and structure	Significant differences in physicochemical properties across breweries ($p < 0.05$) [37]	Lack of process standardization is a major barrier to large-scale valorisation
Post-production handling (drying, storage)	Drying method, transport, storage duration	Alters moisture, microbial activity, and structural shrinkage	Moisture varies depending on drying technique (e.g., 2–10%) [37]	Post-processing introduces secondary variability, often overshadowing raw material effects

barley husk and other non-soluble components, which are naturally high in fiber content. Hemicellulose, which is a polysaccharide, occurs in the largest proportion, followed by another polysaccharide, i.e., cellulose, which is collectively responsible for the high carbon content in BSG, and is closely associated with another important component, lignin, which contributes towards the rigidity of BSG. Victoria Eche et al. [36] stated that the carbohydrates present in BSG are about 60%, of which almost half are present as dietary fibers. This indicates that the biomass has a high concentration of structural carbohydrates rather than simple sugars. Moreover, the complex relationship between these components plays a significant role in determining the thermal and chemical properties of the BSG biomass. Sobek et al. [46] stated that during the pyrolysis process, the BSG biomass decomposes into three different stages, corresponding to the degradation of the individual components of the biomass, namely, hemicellulose, cellulose, and lignin, indicating the structural independence and functional integration of these components in the biomass. Similarly, the presence of various lignin-derived compounds has also been observed to be present in the cell wall matrix of the biomass, which requires intensive treatment to be released, as stated by Niemi et al. [47]. Therefore, the presence of these individual components, namely, cellulose, hemicellulose, and lignin, defines the carbon-rich structure of the BSG biomass, making it suitable for the development of various bioenergy, biomaterial, and carbon-based product applications.

9. Protein and amino acid composition

In addition, Brewer's spent grains are not only a source of structural carbohydrates but also contain considerable amounts of protein, which is characterized by a wide range of amino acids, thus increasing their nutritional significance. Brewer's spent grains contain, on average, a range of 20–30% of dry matter, which is attributed to their protein content. Brewer's spent grains are, therefore, a major source of protein of plant origin. From a nutritional perspective, Brewer's spent grains contain cereal prolamins, hordeins, albumins, and globulins, which are major sources of proteins. According to Ummels et al. [48], Brewer's spent grains contain about 30% of essential amino acids, thus making Brewer's spent grains a source of a balanced mix of amino acids, including considerable levels of amino acids such as leucine, phenylalanine, and valine, each of which contributes about 4–7% of the total amino acids present in Brewer's spent grains. This indicates that Brewer's spent grains can play a significant role in providing essential amino acids for human and animal nutrition. Furthermore, glutamine and proline are among the most abundant amino acids in BSG, making up 30–38.5% of the amino acid composition, and both are representative of the inherent protein composition of barley hordeins, which are resistant to complete hydrolysis. Although levels of sulfur amino acids, including methionine and cysteine, are typically lower, the inclusion of lysine at levels of about 3% is a benefit, as this amino acid is often limiting in many cereal proteins. The above characteristics of the protein composition of BSG highlight the opportunity for this protein source not only to improve the nutritional value of food but also to function as a food ingredient.

10. Lipids, minerals, and micronutrients

The Brewer's spent grains (BSG) have functionally significant but relatively small amounts of lipids, minerals, and other micronutrients, all of which contribute to their carbon-rich content. The major constituents of Brewer's spent grains are structural carbohydrates and proteins, but lipids constitute 10% of the dry matter of Brewer's spent grains, they are of considerable interest because of their triglycerides, free fatty acids, and sterols, among other valuable compounds, including palmitic, oleic, and linoleic acids, which are reported as major fatty acids in Brewer's spent grains based on detailed studies of other grain residues. The interest in Brewer's spent grains' lipids is based on their possible use in biofuel, among other applications, because of their diversity and functional significance. Detailed studies of Brewer's spent grains' lipid composition have reported triglycerides at 67% of their total lipid content, followed by 18% of their lipid content as free fatty acids [36]. Apart from the content of lipids, BSG is also rich in minerals and other micronutrients. The content of minerals and other micronutrients includes calcium, phosphorus, magnesium, iron, copper, potassium, and other essential micronutrients. Phosphorus content is around 6000 mg/kg, whereas the content of calcium is around 3600 mg/kg. Vitamins are also present in the composition of BSG. Vitamins present in the composition of BSG include vitamin B-complex and choline [49]. According to a study by Eche et al. [36] the composition of BSG includes a 10% content of lipids and a high content of minerals. This again validates the fact that the content of lipids and other components, although present in smaller quantities compared to carbohydrates and proteins, plays a vital role in the nutritional and other value-added applications of the by-product. The content of lipids and other components present in the composition of BSG adds more value to the by-product.

11. Polyphenols and bound antioxidants

Brewer's spent grains (BSG), therefore, are now being viewed not only as a fibrous by-product but also as a source of polyphenols and bound antioxidants contributing to their carbon-rich composition and functional potential. The majority of the bound phenolic antioxidants present in the spent grains are phenolic acids, primarily ferulic and p-coumaric acids. They are mainly present as ester linkages to the lignocellulosic composition of the barley husk. The bound phenolic composition is not readily extractable without the application of a hydrolyzing agent. In their bound form, the total polyphenol content present in the bound fractions of the brewer's spent grains may vary over a wide range but may be present in an amount of up to 4.7 mg gallic acid equivalents per gram of dry brewer's spent grains. Ferulic acid is found to be present in more than half of the phenolic profile, followed by p-coumaric acids and other hydroxycinnamic acids. Phenolic acids are bound to the cell walls through the hemicellulose and lignin components [50]. This binding limits the natural antioxidant activity of the phenolic acids unless the bound phenolic acids are liberated by chemical and enzymatic treatments. Verni et al. [51] found that xylanase and fermentation significantly improve the bioavailability of these bound antioxidants by significantly increasing their release and bioaccessibility, thereby improving their activity in relation to free radicals. The potential of BSG is not always correctly estimated due to analytical difficulties in the recovery of its phenolic compounds. Indeed, while crude BSG extracts present a phenolic content lower than hydrolysable compounds, hydrolysable compounds are four to five times higher than crude BSG. These properties of BSG reflect its duality: on one hand, its complex carbon structure; on the other hand, its potential for using its phenolic compounds with antioxidant activity for various industrial applications: food, nutraceuticals, cosmetics, and pharmaceuticals.

12. Implications of carbon composition for valorisation

The carbon-rich composition of brewer's spent grains, primarily consisting of lignocellulosic compounds such as cellulose, hemicellulose, and lignin, is of significant interest for valorising brewer's spent grains for uses other than animal feed. Firstly, brewer's spent grains, having a high carbon content, can be valorised for the production of activated carbon or biochar, which can act as alternatives for carbon-based adsorbents currently derived from fossil fuels (see Table 3). Mussatto et al. [52] showed that activated carbon, derived from brewer's spent grains' lignin, can possess comparable surface areas and adsorbent properties for metal ions, thus proving brewer's spent grains' suitability for use in wastewater treatment. Secondly, brewer's spent grains can be Valorised for the production of carbon-based materials for use in energy storage. The systematic KOH activation of brewer's spent grains' biochar can

Table 3
Major valorisation pathways of brewer's spent grain based on its carbon-rich composition and their industrial and environmental applications.

Valorisation pathway	Underlying carbon-rich feature	Industrial/Environmental implications	Reported outcomes
Activated Carbon Production	High lignin and lignocellulosic carbon content provide a robust precursor for carbonization and activation	Enables production of porous activated carbon with high surface area for adsorption and detoxification applications	Mussatto *et al.* [52] demonstrated activated carbons with BET surface areas up to 692 $m^2 g^{-1}$ capable of adsorbing heavy metals and reducing phenolics in solutions, comparable to commercial carbons.
Energy Storage Materials	Carbonaceous BSG biomass is suitable for conversion into biochars and activated carbons with engineered porosity	Porous carbon materials from BSG can be used in energy storage, catalysis, and pollutant capture	Recent research shows that KOH-activated BSG biochars exhibit properties favourable for use in hydrogen storage, lithium batteries, and solar cells, with tunable porosity via synthesis control [53].
Biochar for Adsorption & Remediation	Thermal carbonization of BSG produces stable carbon structures with abundant micro/mesopores	Biochars and hydrochars from BSG are effective in the adsorption of pollutants such as pharmaceuticals and dyes	Activated hydrochars from BSG achieved a high surface area of over 1500 $m^2 g^{-1}$ and significant acetaminophen removal in adsorption tests [55].
Soil Amendment and Carbon Sequestration	Persistent aromatic carbon structures from lignin in BSG biochar can remain in soil for long periods	Improves soil fertility, water retention and facilitates long-term carbon sequestration	Pyrolysed BSG biochars increase soil carbon pools and reduce nutrient leaching, aligning with circular economy goals and sustainable agriculture [49].
Composite Materials & Biopolymers	Cellulose and hemicellulose fractions can be fractionated into building blocks for composite matrices	BSG fractionation contributes to biodegradable polymers and fillers	Biorefinery concepts use BSG carbon to derive cellulose-based fibres and polymer precursors for sustainable packaging and engineering materials [26].

produce carbon-based materials for use in battery electrodes and supercapacitors, thus showing brewer's spent grains' value beyond their use as a fuel source [53]. However, brewer's spent grains' valorisation must take into consideration the complex, carbon-based matrix. The recalcitrance of brewer's spent grains, primarily consisting of lignocellulose, requires pretreatment or fractionation before valorisation into value-added products, and the cost of processing, such as drying, can offset the valorisation process [54].

13. Industrial processing and fractionation technologies

Industrial valorisation of brewer's spent grains (BSG) is also critically dependent on the availability of efficient processing and fractionation technologies that help unlock the carbon-rich lignocellulosic structure [4]. Conventional drying and milling processes are inadequate for efficient valorisation; instead, innovative pretreatment methods such as alkaline hydrolysis, steam explosion, and enzymatic saccharification are preferred for efficient cellulose and hemicellulose fractionation to access the fermentable sugars and phenolics. Particularly, alkaline pretreatment has been reported to facilitate efficient recovery of ferulic and p-coumaric acids, thereby enhancing the overall recovery efficiency for antioxidants [56]. Two-stage enzymatic pretreatment has also been reported to facilitate efficient solubilization of up to 66% brewer's spent grains biomass for efficient valorisation to produce high-value products such as protein, sugars, and lignin derivatives [49]. Compared with the valorisation of raw brewer's spent grains for material recovery, these pretreatment methods have been reported to show considerable advantages in terms of product yields; however, the high cost associated with these processes is a major constraint for their efficient valorisation at the industrial scale [57].

14. Stabilization, drying, and milling

The fundamental principle behind the industrial processing of Brewers' Spent Grain is related to the stabilization requirement to combat the inherent instabilities associated with BSG, which arise primarily due to the initial high levels of moisture content and nutrient availability, thereby promoting rapid microbial development following mashing [58]. In this context, stabilization is not only essential but also needs to be executed in a time-sensitive manner to avoid spoilage and enhance valorisation opportunities. However, it is important to note that stabilization is best performed through rapid drying processes, avoiding chemical preservation methods that may pose regulatory and cost implications without ensuring long-term stability. Drying is therefore considered to be a key operation for BSG, serving not only to enhance stability but also to prepare BSG for fractionation processes. Empirical results show that drying BSG to 15% dry matter and water activity levels of 0.93 inhibit the growth of microorganisms such as Bacillus cereus, thereby providing a scientifically validated threshold for safe storage [58].

However, the drying step is not only an operational requirement but also an area where trade-offs are made, with temperature increases above 75 °C not only speeding up the rate of moisture removal but also potentially increasing the bioactive compound content, although the risk of protein denaturation and energy inefficiency also increases. As such, convective or hot air drying is commonly used, despite its lower preservation efficiency compared to emerging drying techniques such as freeze drying, which are currently not cost-effective [15]. Although the milling step is considered downstream, it is not only an operational requirement but also an operational transformation that has significant implications for the efficiency of the downstream steps. Fine milling not only increases the surface area for increased extractability but also disrupts the lignocellulosic matrix, allowing for particle size-based fractionation of the extracts into fiber-rich and protein-rich streams [59]. However, excessive milling has the effect of diminishing returns, where the energy required for the operation increases disproportionately compared to the extractability.

Thus, stabilization, drying, and milling should be considered a continuous process, not individual steps. The efficiency of milling is predicated upon previous control of moisture levels, and the viability of drying is predicated upon the desired functionality of milled particles. The technological limitations currently experienced in industry are not based upon a lack of understanding or technological capability but upon the ongoing difficulty in achieving a balance between energy requirements and product quality, which continues to limit BSG's progression from a low-value feedstock to a high-value biorefinery feedstock.

15. Enzymatic hydrolysis and bioconversion

These two processes of enzymatic hydrolysis and bioconversion constitute the major transformation steps in the fractionation of BSG; nevertheless, these processes remain limited by the recalcitrance of lignocellulosic biomass and process inefficiencies in integrating these operations. While it is possible to obtain significant levels of glucose (18.45 ± 1.66 g/L) and xylose (6.38 ± 0.26 g/L) by hydrolysing raw BSG, pretreatment is critical in significantly increasing levels of xylose greater than 10 g/L by using alkaline or ionic liquid pretreatments, confirming that these enzymatic approaches remain inadequate in biomass deconstruction for industrial applications. This is because these enzymatic approaches remain limited by a general limitation in lignocellulosic bioprocessing in which enzyme accessibility, rather than enzyme activity, limits bioprocess efficiency. Significant advancements in process intensification approaches, such as additive-assisted hydrolysis of lignocellulosic biomass, indicate that these approaches can partially alleviate lignin-related inhibition; nevertheless, these approaches come with other limitations, such as microbial inhibition by these additives. Likewise, it is possible to achieve up to 87.9% of glucose recovery by using synergistic combinations of PEG 6000 and cationic polymer additives in lignocellulosic biomass hydrolysis. Similarly, new developments in pretreatment and hydrolysis integration, such as plasma-assisted hydrolysis, have shown a promising 2.14-fold increase in reducing sugar yield (162.90 mg/g vs. 75.94 mg/g), further emphasizing that hydrolysis efficiency is significantly influenced by physicochemical disruption [60].

Bioconversion routes have shown that process integration is critical in defining yield and selectivity in bioconversion. Again, hydrolysis-fermentation integration has shown that $>90\%$ of sugars can be recovered and ethanol concentrations up to 39 g/L (equivalent to 222 L ethanol/ton BSG) can be attained with E. coli, compared to co-culture routes and without any need for detoxification [61]. However, for higher solids loadings (>15% DM), detoxification is still necessary despite improved product yield up to 146.5 g ABE/kg BSG [62]. With respect to the overall concept of biorefinery, BSG hydrolyzates show promising characteristics with respect to the nitrogen content and C/N ratios, thus allowing for the improved production of biochemicals such as butanol (6.7 g/L) and organic acids compared to other feedstocks [63]. However, the question of cost is of utmost importance, and the optimized simultaneous hydrolysis-bioconversion approach for the production of proteins, though showing promising results, is not cost-effective compared to the conventional feed costs (0.69 US$/kg) [64].

16. Solid–liquid and green extraction methods

Solid-liquid extraction (SLE), the original basis for BSG extraction, remains the core process in BSG fractionation, although the relevance of SLE in industrial-scale BSG fractionation is not in the process itself but in the influence, it has on the quality and sustainability of the subsequent steps. Conventional SLE using solvents such as aqueous ethanol or alkaline solvents allows for the extraction of phenolic compounds, proteins, and soluble carbohydrates. However, the efficiency of conventional SLE is inherently compromised by the mass transfer mechanisms. Ethanol-water solvents at 60–80% have been widely used in the extraction of BSG, showing promising results in the extraction of bioactive compounds, although the process is characterized by long

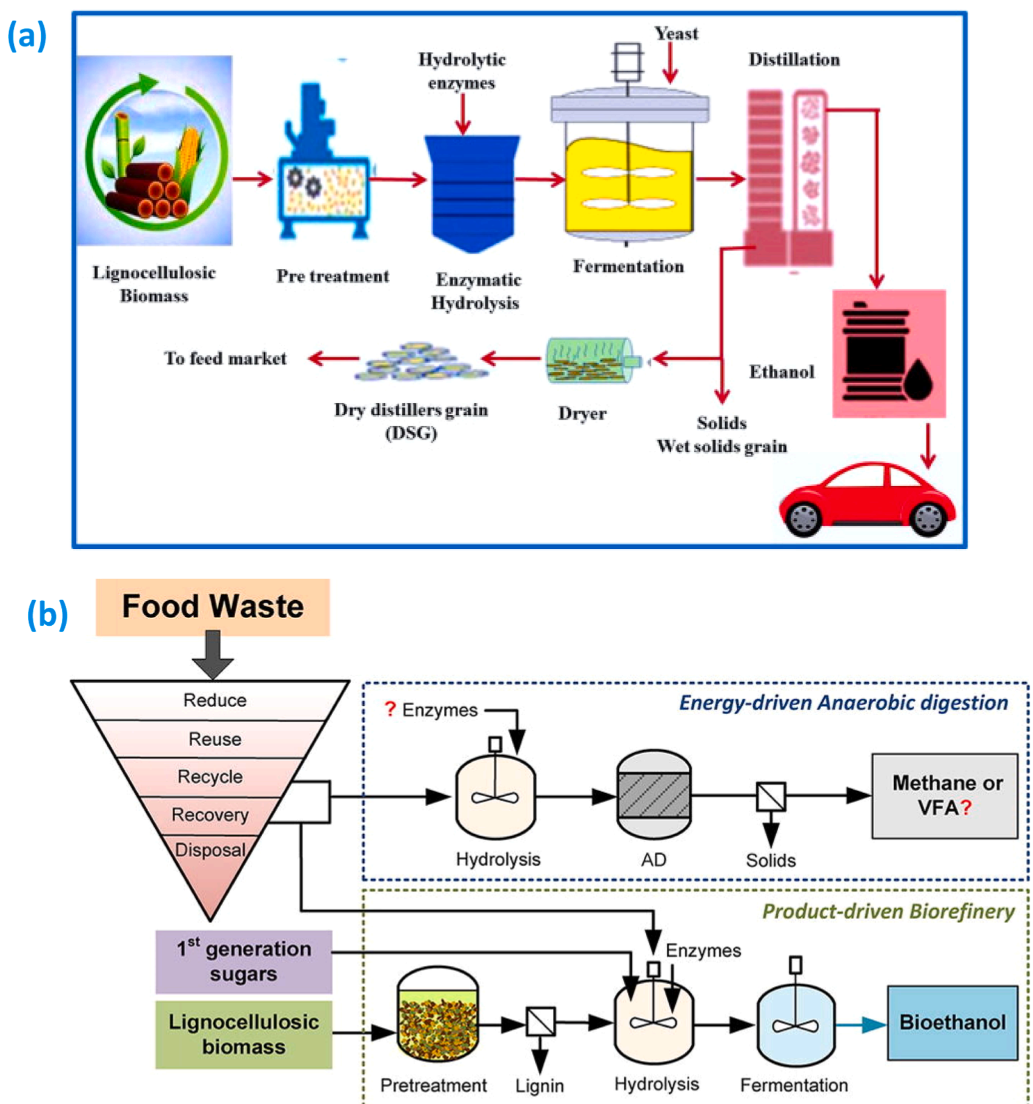

Fig. 2. Schematic representations of biomass valorisation pathways: (a) Lignocellulosic biomass conversion to bioethanol and distillers' grains (Mani Jayakumar et al. [68]), and (b) food waste and lignocellulosic biomass processing in energy- and product-driven biorefineries (Raffel Dharma Patria et al. [69]).

extraction times and the use of high amounts of solvents, compromising the sustainability of the process [65]. This has led to the development of various "green" extraction technologies as process intensification techniques. Despite all these developments, a careful evaluation of the literature reveals that green techniques are not always superior. Although green techniques offer improved extraction efficiency and reduced environmental impact, challenges remain regarding scalability, equipment costs, and overall process efficiency. Furthermore, ultrasound-assisted, microwave-assisted, and subcritical water extraction techniques are known to enhance cell wall rupture and solute diffusion, thus enhancing the efficiency of protein and phenolic compound recovery compared to traditional techniques [28]. Subcritical water extraction, in which water is used under suitable temperature and pressure conditions, allows the solvent to be "tunable" so that no organic solvent is required while maintaining high efficiency [66]. Supercritical CO_2 extraction offers superior selectivity for phenolic compounds compared to Soxhlet extraction, thus promising high-value phenolic compound recovery [67]. Fig. 2 **(a and b)** illustrates the sequential processes of pre-treatment, hydrolysis, fermentation, and product recovery in biorefineries, highlighting both ethanol production from lignocellulosic feedstocks and anaerobic digestion or bioethanol pathways from BSG and food wastes

Energy demand is an important consideration across BSG valorisation pathways, particularly for energy-intensive operations such as drying and distillation. These operations can contribute substantially to overall process energy demand and should therefore be considered when evaluating the environmental and techno-economic feasibility of BSG valorisation routes.

In the same vein, microwave-assisted and ultrasound technologies can improve yields but may also affect the structure and functional properties of the extracted proteins, particularly for applications such as emulsification and gelation. In addition, the difficulty of achieving high purity with both conventional and green approaches suggests that extraction efficiency is not the sole determinant of the process's industrial applicability. The process of solid-liquid extraction (SLE) remains the basis for BSG fractionation; however, the relevance of SLE in industrial applications is not in the process itself, but in the impact it has on the quality and sustainability of the subsequent steps in the process [70]. Traditional SLE, using solvents such as aqueous ethanol or alkaline solvents, facilitates the extraction of phenolic, protein, and water-soluble carbohydrate compounds; however, the process efficiency is inherently limited by mass-transfer mechanisms and solvent solubility. Likewise, ethanol-water solvents in the 60–80 wt% range have been reported as effective in BSG extraction, showing promising results in the extraction of bioactive compounds; however, the process requires long extraction periods and high solvent usage, which in turn affects the sustainability of the process [28].

Thus, green extraction technologies have come to be recognized as intensification strategies for improving extraction rates while minimizing solvent and energy use. The solid-liquid extraction (SLE) process for brewer's spent grain (BSG) needs to be critically understood as an essentially structurally dependent process in which efficiency is not dictated by the choice of solvent alone, but by physicochemical treatment of the lignocellulosic material. The native brewer's spent grain is characterized by high levels of lignin content (30.84 g/100 g) and an ordered fibrillar structure. The inherent nature of brewer's spent grain limits the rate of solvent penetration and diffusion into the solid particles, thus dictating the efficiency of extraction. The limitations in brewer's spent grain extraction by SLE explain why intensification strategies involving pretreatment-assisted extraction processes consistently achieve much higher efficiencies than SLE. Similarly, hydrothermal-based green processing, such as instantaneous controlled pressure drop (DIC), has shown that structural disruption is a direct correlate of extraction efficiency, where near-complete hydrolysis yields of around 100% can be achieved under optimized conditions of 5–7 bar and 15 min, compared to a very poor yield of BSG when untreated [71].

These observations further emphasize that for successful SLE of BSG, it is a structure-enabled, rather than a solvent-enabled, extraction process. However, there is a trade-off in increasing pretreatment severity, as high-severity conditions for BSG lead to degradation products such as furfural (15.73 g/L) and HMF (8.56 g/L), affecting the purity of the final extracts for further use [72].

In contrast, green extraction technologies aim to balance high efficiency in the SLE of BSG by combining mild solvents with improved mass transfer. Subcritical water- or ethanol-organosolv-based technologies can enable selective lignin removal of up to 44.69%, thereby enhancing the selectivity of solid–liquid fractionation of BSG without relying on harsh chemicals [72]. Yet a major limitation remains: although these strategies enhance sustainability performance, they do not eliminate the need for pretreatment severity to achieve maximum yields. From a broader perspective on bioprocessing, it is also important to note that enzymatic systems, which are critical to both extraction and valorisation, are highly sensitive to substrate accessibility. This again points to the importance of creating optimal environments for extraction. As with other biomass systems, enzymatic systems are directly affected by structural openness and environmental factors. Therefore, the shift from conventional SLE to green extraction in BSG processing should not be regarded as a simple technological replacement but rather as a systems optimisation problem. In fact, the most effective industrial approaches to processing BSG combine mild SLE with intensified green approaches. This is particularly important in the development of BSG from a low-value waste product to a sustainable feedstock within the circular economy.

17. Fermentation and microbial upgrading

Fermentation and microbial upgrading of Brewers' Spent Grain (BSG) are key processes in which sugars and nutrients are converted into fuels, chemicals, and biomass; however, the process is more dictated by microbial selection and process conditions than by the actual fermentation. BSG is naturally rich in fermentable carbohydrates such as cellulose and hemicellulose and has a favourable nitrogen profile, making it not only a carbon source but also a nutrient-rich medium that can replace the need for supplementation in microbial cultivation. In fact, the process of ethanol production has been the most studied and has demonstrated high efficiencies in hydrolysis-fermentation systems. In a study as presented in Table 4, Rojas-Chamorro et al. [61] demonstrated that fermentation of pretreated BSG hydrolysates using Escherichia coli can produce ethanol concentrations of up to 39 g/L, which translates to over 220 L of ethanol per ton of BSG without detoxification steps. This demonstrates the advantage of single-organism systems in facilitating easier integration of fermentation processes. Moreover, optimisation of fermentation using hydrolysates can produce ethanol with yields of up to 82% of the theoretical maximum, which confirms that BSG can compete with conventional lignocellulosic biomass if adequate control is exercised in the fermentation process [67].

In addition to ethanol production, microbial upgrading routes can also produce other valuable chemicals such as butanol, organic acids, enzymes, and single-cell protein. This is a true reflection of the potential of BSG in various circular economy schemes. In this context, it is important to note that the choice of microorganism is critical. Although Saccharomyces cerevisiae is quite robust for hexose metabolism, alternative microbes such as E. coli and mixed cultures can produce better results when using pentose sugars. This is because co-culture systems can produce undesirable stability issues that can compromise overall yield [61]. Consequently, integrated biorefinery frameworks are increasingly designed to incorporate complementary fractionation, enzymatic hydrolysis, and microbial conversion strategies to enhance substrate utilization efficiency and stabilize product formation (as illustrated in Fig. 3). One of the limitations in industrial-scale fermentation is that inhibitory compounds, such as phenolics and furfurals, may be present in the pretreated substrate, affecting microbial activity

Table 4
Fermentation and microbial upgrading pathways in BSG biorefineries.

Process/Pathway	Microorganism/System	Key operating features	Performance metrics	Analysis & critique	Industrial implication
Ethanol fermentation (Integrated hydrolysis–fermentation)	*Escherichia coli*	Whole slurry fermentation after acid pretreatment; no detoxification required	Up to 39 g/L ethanol; 222 L/ton BSG [61]	High efficiency due to simultaneous utilization of hexose and pentose sugars; monoculture avoids metabolic competition seen in co-cultures	Promising for scale-up; reduced process complexity, but still dependent on pretreatment efficiency
Consolidated bioprocessing (CBP)	*Aspergillus oryzae* + *Saccharomyces cerevisiae*	Simultaneous enzyme production, hydrolysis, and fermentation without external enzymes	Up to 37 g/L ethanol under optimized conditions [41]	Eliminates enzyme cost, but slower kinetics and longer residence times limit industrial throughput	Suitable for low-cost decentralized systems; trade-off between cost and productivity
Simultaneous Saccharification and fermentation (SSF)	*Saccharomyces cerevisiae*	Operated at 15% solids; integrated enzymatic and fermentation steps	21 g/L ethanol, 74% theoretical yield [73]	Process integration improves yield but is limited by enzyme inhibition and mass transfer constraints at high solids	Widely applicable industrial strategy; requires optimization for high-solids processing
Sequential hydrolysis–fermentation (SHF)	Yeast systems	Separate enzymatic hydrolysis followed by fermentation	Up to 22.5 g/L ethanol, 72% theoretical yield [74]	Better control over each stage, but increases operational complexity and cost	Preferred at higher solid loading, where process control is critical
ABE fermentation (Butanol pathway)	*Clostridium acetobutylicum*	Fermentation of hydrolysates rich in mixed sugars	12.6 g/L ABE, 79% sugar conversion [75]	Produces higher-value fuels than ethanol, but is sensitive to inhibitors and requires strict anaerobic control	Industrial potential for advanced biofuels, but economically constrained by process sensitivity
Yeast-based fermentation (Nutrient utilization)	*Saccharomyces cerevisiae*	Utilizes intrinsic nitrogen in BSG; minimal supplementation required	12–13 g/L ethanol without supplementation [76]	Demonstrates BSG's dual role as a carbon and nutrient source; however, productivity is lower compared to engineered systems	Reduces nutrient cost; suitable for low-input fermentation systems

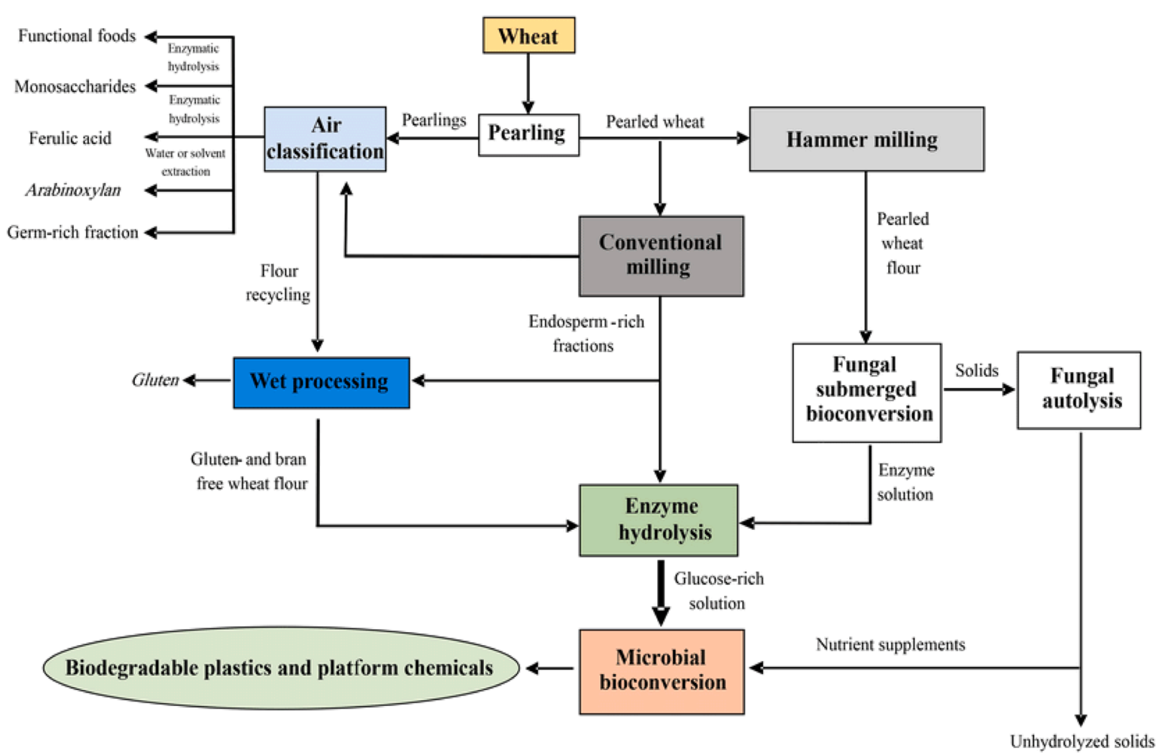

Fig. 3. Schematic diagram of a wheat-based biorefinery for air classification, milling, enzymatic hydrolysis, and microbial bioconversion for the production of biodegradable plastics, platform chemicals, and functional food components (adapted from Abdul Manan and Webb, [77]).

and thus requiring additional unit operations for detoxification. Furthermore, high solid loading, although beneficial for achieving high product titers, may be a limitation in terms of scalability due to mass transfer and inhibition effects. Fermentation and/or microbial upgrading of BSG are not independent unit operations but part of a larger integrated biorefinery concept, where success is achieved by matching conditioning, metabolism, and reactor engineering. At present, the challenge is in achieving a balance in terms of yield optimization, robustness, and economic viability, especially when moving from efficiency to consistency at an industrial scale.

18. Emerging thermal and non-thermal

Newly developed thermal and non-thermal technologies are increasingly redefining the industrial processing and fractionation of brewer's spent grains, shifting the focus from conventional thermal to more selective and quality-conserving routes. Although conventional thermal treatments like steam explosion and hydrothermal treatment are effective in disrupting the lignocellulosic structure, they are associated with partial degradation of hemicellulose-derived sugars and phenolic compounds, thus limiting the efficiency of downstream Valorisation. Conversely, recent advances in controlled thermal technologies, including microwave-assisted and infrared heating, have successfully provided rapid volumetric heating, thereby more efficiently disrupting the cell wall structure to release arabinoxylans and phenolics with shorter residence times and reduced thermal gradients. However, these routes are also associated with potential risks of local overheating and structural degradation of biopolymers. Therefore, there is a growing need to explore more selective routes. As presented in Table 5**,** non-thermal technologies have been found to provide more targeted routes for the fractionation of brewer's spent grains. Ultrasound has been found to disrupt the lignocellulosic structure, thereby providing a more effective route for extracting proteins and phenolic acids.

Pulsed electric field processing is another technique that complements this by permeabilising membranes, thereby enhancing mass transfer efficiency without affecting bulk temperatures. High-pressure processing has been identified as a potential means of altering protein structures in BSG, thereby enhancing solubility. Cold plasma, although in its infancy, has shown promise in altering BSG structures by introducing reactive species that can be used for surface modification and partial depolymerisation, thus enhancing enzymatic accessibility. Saydul Md. Safwa et al. [78] found that non-thermal technologies are significant for preserving the nutritional and sensory attributes of BSG, thereby minimising thermal stress, which is very important for the retention of BSG bioactive compounds. Despite the potential of these technologies for BSG processing, integrating them into BSG processing systems remains challenging. A harmonised approach that combines mild thermal pre-treatment with non-thermal intensification may be a potential route for BSG fractionation.

19. Valorisation of BSG into food ingredients

Brewer's spent grain (BSG), the major by-product of beer brewing, has now expanded beyond its conventional role as animal feed to be valorised as an ingredient in human food products. Brewer's spent grain is rich in dietary fibres (50% of its carbohydrate content), proteins (30%), minerals, and phenolic compounds. Brewer's spent grain has an added advantage over other ingredients in food products in terms of its high fibre and protein content, making it suitable for use in baked goods, beverages, and various food products [36]. Brewer's spent grain has limitations in its use in food products in terms of its high fibre content, which affects its hydration properties in dough, gluten, and texture; Brewer's spent grain is not suitable for use in amounts greater than 15% in food products, as it affects acceptability by consumers [84], [85]. Fig. 4 displays various processing, pretreatment, and valorisation routes of brewer's spent grain (BSG). This figure demonstrates the routes of alkaline pretreatment and structural modification of the spent grain, the integration of the brewing process with the spent grain, the routes of enzymatic and fermentation conversions of the spent grain, and the possibility of using the spent grain as a functional food ingredient.

The Brewer's Spent Grain (BSG), which is traditionally regarded as a waste product of beer production, is also seen to have tremendous potential for Valorisation. Recent studies have also indicated that Brewer's Spent Grain is a rich source of dietary fibre, proteins, and other bioactive compounds. Hao-Yu Ivory Chu et al. [90] have also indicated that Brewer's Spent Grain can produce a high percentage of extracted compounds, such as total dietary fibre (93.3%), individual dietary fibres such as hemicellulose (54.9%), lignin (69.5%), and cellulose (88.3%). In addition to this, the extracted bioactive compounds, such as fatty acids like oleic acid, linoleic acid, palmitic acid, and phenolics like gallic acid, catechol, and vanillin, can also be used for the production of functional foods and nutraceuticals. Rosa Leonor González-Díaz et al. [91] have further demonstrated that BSG can be used to improve nutritional and techno-functional characteristics of food products by incorporating it in a fungal fermentation process or a bread recipe. BSG was identified for its high protein content of 19.66 g/100 g and high soluble fibre content of 15.87 g/100 g, and bread recipes that used BSG at partial substitution levels were identified for high sensory acceptance. Daniela Lamas and Brenda Gende [92] further reported that the BSG protein beverage has a protein content of more than 3%, and that the BSG used in bread recipes has a high dietary fibre content, ranging from 1.5% to 3%. Research also

Table 5
Emerging Thermal and Non-Thermal Plasma Technologies in BSG Processing and Fractionation.

Technology type	Process/technique	Operating principle	Performance data	Analysis & limitation	Effect on industrial application
Thermal (Hydrothermal pretreatment)	Hydrothermal processing (water under high temperature/pressure)	Autohydrolysis disrupts the lignocellulosic matrix without chemicals	Methane yield increased by > 200%; 30% increase in volatile solids degradation [79]	Effective and scalable; avoids chemicals but may generate inhibitors at high severity	Suitable for large-scale waste-to-energy and biorefinery integration
Thermal (Microwave-assisted hydrothermal)	Microwave heating with water (no catalysts)	Rapid internal heating enhances biomass deconstruction and solubilization	82% sugar recovery (43 g sugars/100 g BSG) [80]	High efficiency and reduced processing time; however, uneven heating and scale-up challenges persist	Promising green alternative for rapid fractionation and sugar recovery
Thermal (Microwave-assisted alkali)	Microwave + mild alkali	Combined thermal–chemical disruption improves delignification	2.86-fold increase in sugar yield (228 vs. 79 mg/g BSG) [81]	Highly effective but introduces chemical dependency; compromises green classification	A hybrid approach balancing efficiency and cost in industrial pretreatment
Non-thermal plasma pretreatment	Dielectric barrier discharge plasma	High-energy ionized gas induces surface oxidation and delignification	Significant increase in hydrolysis efficiency and fermentability [60]	Chemical-free and rapid; however, energy cost and reactor scalability remain limiting	Emerging high-value applications in advanced biorefineries
Non-thermal (Ultrasound pretreatment)	Acoustic cavitation (20–1000 kHz)	Bubble collapse disrupts biomass structure and enhances mass transfer	Methane content up to 56% in biogas; improved digestibility [82]	Enhances accessibility, but energy input may offset sustainability gains	Effective as a preconditioning step in anaerobic digestion systems
Hybrid thermal–carbonization	Hydrothermal carbonization (HTC)	Converts wet biomass into hydrochar under subcritical conditions	Improved carbon-rich solid fractions and surface functionality [83]	Produces value-added solids but reduces fermentable carbohydrate availability	Suitable for material applications rather than biochemical conversion

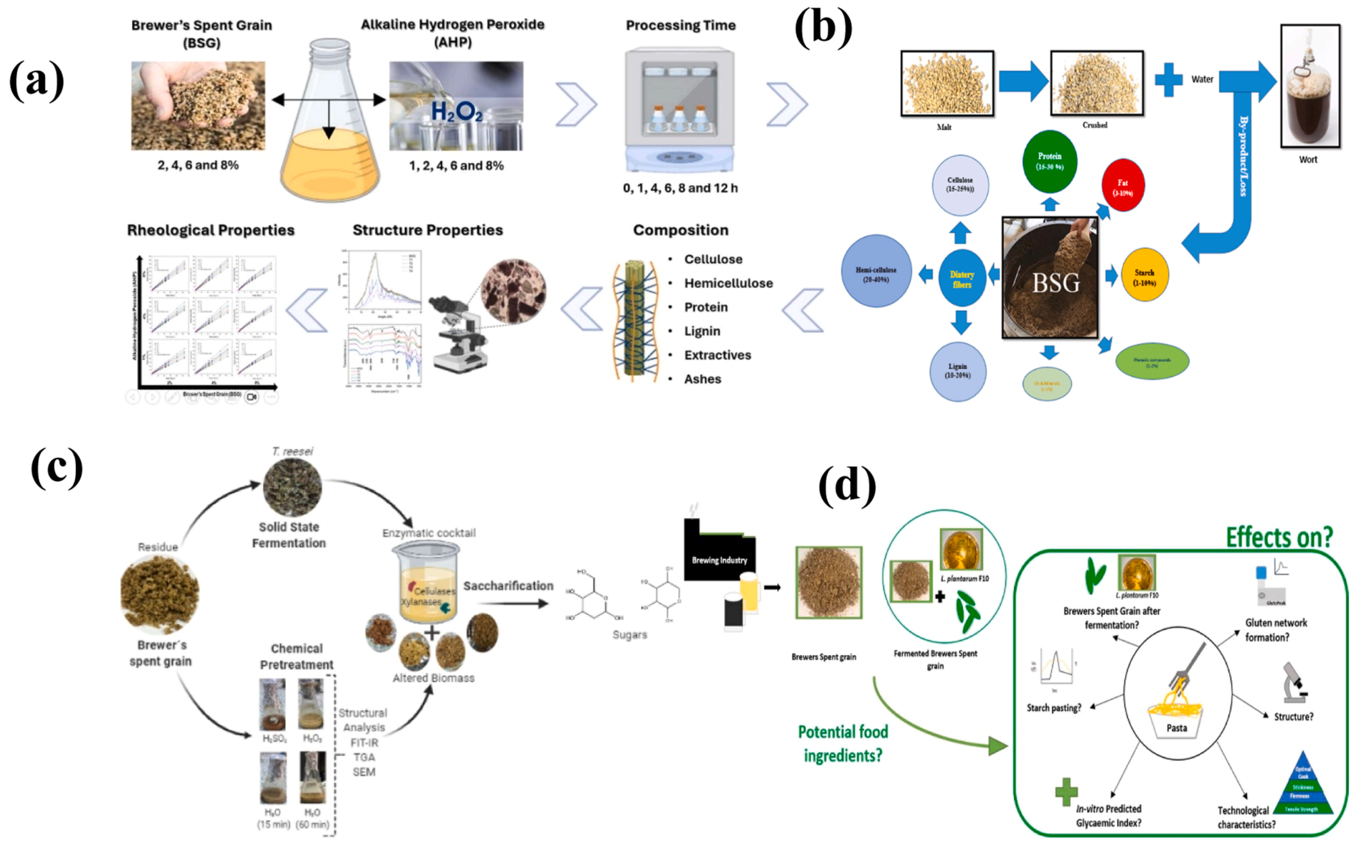

Fig. 4. Overview of brewer's spent grain (BSG) processing and valorisation pathways: (a) alkaline hydrogen peroxide pretreatment and structural characterization (Marcio Augusto Ribeiro-Sanches et al. [86]; (b) brewing process generation and BSG composition (Hamed Saberian et al. [87]); (c) enzymatic hydrolysis and fermentation for sugar and biofuel production (Evelyn Wagner et al. [88]); (d) potential food ingredient applications and functional effects in food systems (Emma Neylon et al. [89]).

shows the potential of BSG flour to reduce fat and sugar content in food products while enriching nutritional value. Studies have also examined the potential of using water fractions and protein hydrolysates in the development of bread, snacks, and ready-to-drink beverages [93]. However, research also shows the constant compromise between nutritional benefits and sensory attributes (see Table 6). Although fibre and protein content align with the latest consumer trends, sensory attributes need to be enhanced through pre-treatments such as fermentation or extrusion to make the product more appealing to consumers. However, the lack of large-scale processing facilities and inconsistent raw material quality pose serious bottlenecks to the commercialisation of BSG [94].

20. Dietary fibres and prebiotic ingredients

Brewer's spent grain (BSG) has shown considerable promise as a

Table 6
Valorisation of Brewer's Spent Grain (BSG) into Food Ingredients.

Category	Valorisation route/food ingredient	Key functional/Nutritional contribution	Real-world examples	Analysis & critique
Flours & bakery additives	Dried & milled BSG flour as a partial flour substitute	Adds dietary fibre (mainly arabinoxylan, β-glucan) and proteins to baked foods	Bread, cookies, muffins, crackers enriched with BSG flour	Increases fibre and protein but can alter texture and sensory attributes at higher inclusion levels; optimal incorporation is often ≤ 15% for acceptability [36].
Protein enrichments	BSG protein concentrates/ extracts	Adds plant-based protein, useful for fortification	Protein beverage bases, protein-enriched pasta, or cereals	Strong source of plant protein; however, the extraction cost and techno-functional properties (solubility, emulsification) vary depending on the extraction method [95].
Functional beverages	BSG-based protein or fiber drinks	Soluble fiber and bioactives (antioxidants)	Ready-to-drink protein/ fiber beverages	Shows potential for beverage development; research demonstrates moderate protein enrichment, but industrial scalability and consumer acceptance are still under study [92].
Fat/Sugar replacement	Use of BSG flour as a fat/ sugar replacer in formulations	Reduces caloric density and increases fiber content	Low-fat cookies, snacks	May help meet health claims, but texture modification can be challenging and may require pretreatment or ingredient balancing [96].
Fermented BSG ingredients	BSG as a fermentation substrate	Produces value-added bioactive compounds and prebiotics	Fermented BSG fibers for enriched foods	Fermentation increases bioactive potential, but processing complexity increases; industrial adoption remains limited [18].
Bioactive/ Functional enrichment	Extraction of phenolics and antioxidants	Provides potential health benefits such as antioxidant activity	Functional ingredient isolates for food fortification	Health benefits depend on extraction efficiency and compound stability; variability in bioactive content is a challenge for consistent industrial use [97].

dietary fibre and prebiotic ingredient, owing to its complex polysaccharide composition and fermentability. In BSG, 40–60% is made up of dietary fibre, including cellulose, hemicellulose, and lignin. In the context of prebiotic functionality, arabinoxylan (AX) plays a crucial role in modulating the gut microbiota. Research by Mursalin Sajib et al. [98] established the feasibility of obtaining up to 57% of the AX component, which is converted into arabinoxylooligosaccharides via enzymatic action, thereby selectively promoting the growth of beneficial microorganisms such as Bifidobacterium adolescentis, comparable to the rates observed in the use of fructooligosaccharides. In addition to extraction, fermentation strategies further improve BSG's prebiotic activity. According to Marcos Barrera-León et al. [99], solid-state fermentation improves the bioavailability of fibers, producing prebiotic metabolites, and simultaneously decreases anti-nutritional compounds, increasing antioxidant activity. This improves the functional relationship between BSG's fibres and gut health, including increased production of short-chain fatty acids, such as acetate and propionate, which are essential for metabolic regulation. However, this functional relationship has its limitations. For one, BSG's heterogeneous composition may promote less beneficial microorganisms, and, in its raw form, it may adversely affect food texture and palatability, thus necessitating modification of its fibres.

21. Protein concentrates and bioactive peptides

Brewer's spent grain (BSG), as a cheap source of protein concentrates and bioactive peptides, has received increasing interest in recent years, but the successful valorisation of BSG is heavily reliant on the process route, which can optimise the functionality and bioactivity of BSG-derived proteins. In fact, BSG-derived proteins are characterised by a highly complex structure and poor solubility, making their direct use difficult; however, the extraction process plays a significant role in optimising their performance. In fact, as reported by Yi Ling Chin et al. [100], the use of the enzymatic-assisted extraction process allows the production of low molecular weight peptides (<10 kDa), which are completely soluble and characterized by high emulsifying activity (83 m^2/g) and antioxidant activity, whereas the use of alkali and ethanol solvents in the extraction process allows the production of insoluble proteins, which are characterized by high water-holding capacity (2.5–4.0 g/g). Further refinement through enzymatic hydrolysis enhances the techno-functional and physiological properties of the proteins. Nooshin Bazsefidpar et al. [101] established that optimised hydrolysis resulted in a yield of up to 64.53% proteins with enhanced solubility (47.56%), emulsification activity (85 m^2/g), and appreciable antioxidant and α-glucosidase inhibitory activity, making them viable for metabolic health-related applications. Alternatively, the proteins can be fermented to enhance their availability and activity. Yi Ling Chin et al. [70] established that proteins derived from fermented BSG contained 61–66% protein and exhibited superior emulsification, foaming, and antioxidant activity, with proven stability in complex food matrices such as mayonnaise, making them viable as multifunctional food ingredients.

From a nutritional perspective, proteins derived from BSG have a competitive bioavailability profile. Meeke Ummels et al. [48] established that the amino acid uptake of BSG proteins in the postprandial state reached 69% of whey and 87% of pea proteins, making them viable in the development of plant-based proteins, particularly in a blend to compensate for amino acid deficiencies. In addition, bioactive peptides, such as those with antihypertensive, antioxidant, and antidiabetic effects, further emphasise their functional potential. Maria Cermeño et al. [102] isolated bioactive peptides, such as IPY and LPLQP, that possess strong inhibitory activity against ACE and DPP-IV. Despite these advancements, challenges persist regarding cost, variability, and scalability. Therefore, although BSG protein concentrates and bioactive peptides are multifunctional and sustainable ingredients, their successful translation into industry will require optimisation of efficiency, consistency, and cost-effectiveness.

22. Polyphenol-rich extracts and antioxidants

Brewer's spent grain (BSG) is a potential source of polyphenol-rich extracts and antioxidants, but its valorisation is significantly influenced by the intricate lignocellulosic structures and efficiency of extraction methods. BSG is known to possess a range of phenolic compounds, including ferulic, p-coumaric, caffeic, and syringic acids, and flavonoids such as catechin, mostly associated with lignocelluloses, thus necessitating their degradation for extraction [50]. Therefore, extraction is a crucial step in controlling BSG Valorisation. According to Carciochi et al. [103], optimisation of hydroalcoholic extraction, particularly by increasing ethanol concentration to about 72% at 80 °C, significantly improves polyphenol yield and antioxidant activity, whereas techniques such as ultrasound and microwave accelerate the rate of extraction. In terms of functional aspects, it is evident that the antioxidant activity of BSG extracts is significantly correlated with their phenolic content, thereby confirming their role in controlling free radical activity. According to Zuorro et al. [104], the antioxidant potential of the phenolic-rich extracts obtained using the acetone-water or ethanol-water solvent systems is significant, which confirms their use as potential food preservatives. However, the relatively low total phenolic content in the raw extracts (2.8–3.8 mg GAE/g) warrants the use of various pre-treatment techniques such as alkali hydrolysis and heat treatment [50].

Processing interventions: Various interventions during processing further refine the antioxidant potential. Heat treatment has been reported to increase total phenolic content by up to twofold and significantly improve antioxidant activity through the degradation of lignin-carbohydrate complexes. Similarly, bioprocessing/fermentation has been reported to enhance antioxidant activity through the release of bound phenolics and their synergistic interactions [105]. Nonetheless, challenges persist in the use of BSG. The diversity in BSG composition may affect the quality of the extracted products, while the extraction conditions may also affect their food-grade status. Furthermore, the need to develop efficient, green, and scalable technologies for the extraction of the products also presents a challenge in the adoption of BSG-based products in the food industry. Despite the availability of a sustainable source of antioxidants in the form of BSG-based polyphenols, the challenge of developing a functional product in the food industry still exists.

23. Applications in bakery, beverages, and meat alternatives

Brewer’s spent grain (BSG) is increasingly being valorised as an effective multifunctional food ingredient in bakery products, beverages, and meat substitutes, especially because of its high content of dietary fibre (40–50%) and protein (15–30%), thus improving food system nutrient content [87]. In bakery products, BSG is generally used as an alternative to wheat flour in bread, cakes, and biscuits. The addition of BSG has greatly improved the content of fibre, minerals, and protein in baked products. As presented in Table 7, it has also posed technological challenges in gluten content, crumb texture, and colour, thus restricting its addition to moderate levels [106]. The addition of BSG to beverage products has provided an added advantage in food formulation, especially due to its soluble content. Brewer’s spent grain has been successfully incorporated into beverages such as protein drinks and has not posed any technological challenges, unlike in solid food products [84]. Nevertheless, challenges related to flavour masking, stability, and consumer acceptability of waste-derived ingredients pose hurdles to commercialisation, suggesting that formulation strategies need to be extended beyond nutritional optimisation. In meat analogues, BSG has dual functions in improving nutritional content and physical properties. BSG, in addition to plant-based meat analogues, improves fibre content, protein digestibility, and texture. In fact, Silva et al. [107] observed that

Table 7
Applications of BSG in Bakery, Beverages, and Meat Alternatives.

Application area	BSG utilization strategy	Functional & nutritional contribution	Evidence-based findings	Technical assessment
Bakery products (Bread, biscuits, nnacks)	Partial substitution of wheat flour (5–20%) with BSG flour	Enrichment with dietary fibre (up to 50%) and protein (15–30%), reduced glycaemic response	Bread enriched with BSG shows increased fibre, protein, and antioxidant capacity, but higher inclusion increases crumb firmness and reduces acceptability [87]	Nutritional enhancement is consistent; however, technological constraints (gluten dilution, darker color, texture hardening) limit inclusion levels (10–15% optimal), reflecting a functional–sensory trade-off requiring pre-treatment strategies
Bakery (General food systems)	Use of BSG as a functional ingredient in cereal-based foods	Provides bioactive compounds, essential amino acids, and minerals	BSG is widely applied in bread, cookies, cakes, pasta, and cereal products due to its nutrient density [108]	Demonstrates strong versatility across bakery systems, yet variability in raw BSG composition affects product consistency, highlighting the need for standardization and controlled processing
Beverages (Protein/Fibre drinks)	Incorporation of BSG extracts or slurry into beverages	Supplies > 3% protein and soluble nutrients, supports plant-based beverage innovation	BSG-based beverages contain 3.26% protein and acceptable physicochemical properties [92]	Beverages overcome texture limitations seen in solid foods, but challenges persist in flavor masking, stability, and consumer perception of waste-derived ingredients
Fermented & functional beverages	Use of BSG in cereal-based or fermented drinks	Enhances digestibility, bioavailability, and functional compounds	BSG contributes to the development of non-dairy, plant-based beverages aligned with dietary trends [92]	Strong alignment with vegan and functional food markets, though processing complexity and shelf-life stability remain critical barriers
Meat alternatives (Plant-based analogues)	Incorporation of BSG (10–15%) into soy-based or extruded meat analogues	Improves dietary fibre content, protein digestibility, and texture modulation	At 15% inclusion, BSG improves texturization and digestibility, but higher levels impair fibrous structure and sensory quality [107]	Indicates a dual role as nutritional enhancer and structural modifier, yet excessive inclusion disrupts meat-like texture, requiring formulation balance
Hybrid/Processed meat products	Use as an extender or fat replacer in meat formulations	Enhances water-holding capacity and nutritional profile	BSG application extends to low-fat meat products and meat analogues [108]	Supports clean-label and sustainability trends, but coarse fibre and flavor impact necessitate refinement or blending strategies

15% BSG addition improves texturisation and reduces hardness, although excessive amounts deteriorate fibrous texture and sensory properties. In addition, various reviews have demonstrated the increasing use of BSG in sausage products, burgers, and plant-based analogues, thus underlining its acceptability in various protein-based products.

24. Valorisation of BSG in animal feed and aquaculture

Brewer's spent grain has been utilised in ruminant nutrition as a dietary fibre source. Brewer's spent grain is composed of lignocellulose and has been shown to improve the fermentation process in ruminants. Brewer's spent grain residues have been shown to have improved neutral detergent fiber digestibility following protease treatment, and this has been attributed to the suitability of the waste in ruminant nutrition despite the reduced dry matter digestibility following enzymatic treatment [109]. Brewer's spent grain is effective in aquaculture feeds and has been proposed as an alternative nutrient source, replacing conventional sources such as fishmeal. Brewer's spent grain has been shown to support the healthy development of fish and has been attributed to the increased gut microbial diversity of the fish. Brewer's spent grain has been shown to increase the levels of beneficial gut microbes such as Lactobacillus and Bifidobacterium [110]. Additionally, partial replacement trials in fish such as seabream have demonstrated that an inclusion rate of up to 15% in fish diets is effective in sustaining growth performance and feed conversion efficiency comparable to commercial diets, with protein digestibility values ranging from 89% to 95% [111]. The valorisation of BSG residues has also been demonstrated by Osei et al. [112], who reported that BSG has good potential for valorisation as ruminant feedstuffs through improved fibre digestibility by enzymatic treatment. Another challenge has been addressed by Jin-Xiong et al. [113], who demonstrated that BSG inclusion in fish diets improves gut microbial diversity and biosafety, thus addressing its dual role in fish nutrition. Despite these challenges, there is still room for improvement in addressing issues such as composition, moisture content, and balance in amino acid content.

25. Use in livestock and poultry

In livestock production, BSG valorisation offers nutritional and economic benefits. BSG contains a significant proportion of protein, ranging from 15% to 26% on a dry matter basis, that complements forage-based diets in ruminants, providing essential amino acids when effectively incorporated into animal feeds. For ruminants, such as cattle, BSG provides a suitable proportion of dietary fibers and protein for ruminal fermentation. Furthermore, breeding studies and feed analyses indicate that the valorisation of BSG could improve milk production and quality in dairy farming compared with conventional high-energy feedstuffs such as maize [114]. In the context of poultry farming, especially broilers and layers, the valorisation of BSG seems to require a more differentiated approach to understanding its role in feed and its physiological effects on birds [115]. Recent scientific evidence points to the fact that the valorisation process of BSG, especially when up to 20% fermented BSG is added to the broiler feed, could improve the development of the intestines and ensure sufficient growth performance, especially if the grain is subjected to biological treatment to improve the accessibility of nutrients [112], [116], [117]. Nevertheless, it is worth noting that inclusion rates above this level may negatively affect growth and conversion efficiency owing to the high fibre content, which is generally less digestible in monogastric species such as chickens [118], [119]. Moreover, these findings demonstrate both the potential and limitations of BSG in poultry production, underscoring the need for BSG to be processed by fermentation for effective use. Most significantly, these findings demonstrate a paradigm shift in agricultural research focused on harnessing the potential of circular economies for agro-industrial by-products. By harnessing BSG, it is possible to reduce the footprint of brewery waste streams, which generally negatively influence the environment owing to the production of greenhouse gases [114], [120]. For livestock producers, BSG is a potential ingredient in animal feeds owing to its nutrient content, underscoring that it can be harnessed through a variety of strategies that enhance nutrient uptake.

26. Fish Feeds

Firstly, in terms of nutrient composition, BSG has a high potential for being used in fish feeds, given that it has a high protein content. This is one of the main reasons why BSG is of interest in terms of being a potential alternative to traditional protein sources such as fishmeal and soybean meal, given that these sources are becoming more and more expensive. As Karlsen et al. noted in their comprehensive review, BSG is "a potential, unrealised protein source for aquaculture feeds, given its assured availability every year, its relatively low market cost, and its protein content." However, this potential is closely linked to its limitations, one of which is its high content of lignocellulose and non-starch polysaccharides, which are poorly digestible by fish [121]. Such a dichotomy between potential and limitation is evident in various empirical trials. To exemplify this, Chattaraj et al. [111] conducted an eight-week feeding trial on Cirrhinus reba, incorporating BSG meal into the diet. The results were impressive, showing that fish fed BSG meal had significantly higher growth parameters and no pathological symptoms, indicating biosafety and growth promotion in fish diets. The diversity of the gut microbiome was also greater, with beneficial microorganisms such as Bacillus and Lactobacillus more dominant. The results not only prove the feeding value of BSG but also its potential as a prebiotic in fish diets. The structural fibre in unprocessed BSG makes it difficult for nutrients to be absorbed. Excessive levels of BSG in carnivorous fish diets have also been found to be detrimental to growth performance. Valorisation in such instances has taken the form of various processes, including enzymatic treatment, microwave treatment, and solid-state fermentation (SSF). It may involve enhancing nutrient availability, where microwave-treated BSG diets were noted for enhanced growth and feed efficiency in gilthead sea bream compared to untreated BSG. These technological advancements are crucial in fine-tuning BSG's nutritional value, moving away from direct inclusion [122]. An illustrative case of this analytical shift in valorising BSG is solid-state fermentation, where BSG valorisation enhances its protein content and concurrently reduces its indigestible fibre content, thus rendering it more suitable for both omnivorous and carnivorous fish species. Valorisation, in this case, is a holistic concept, moving away from simply reusing a by-product [123].

27. Safety, quality, and regulatory considerations

The Brewer's Spent Grain (BSG) feed valorisation is strongly dependent on safety and quality issues that are interlinked with regulatory aspects, which are critical for assessing its feasibility beyond being a waste product. One of the safety issues associated with Brewer's Spent Grain is its high moisture content. Brewer's Spent Grain is highly perishable when fresh. In fact, if Brewer's Spent Grain is not dried quickly, it is prone to fungal growth (see Table 8). This indicates that Brewer's Spent Grain is not only perishable when fresh but also that its valorisation is not merely about reusing it [124]. In addition to microbial contamination, mycotoxin contamination is also a critical safety and quality issue. Barley is highly prone to mycotoxin contamination. In fact, Fusarium and Aspergillus can produce mycotoxins such as zearalenone (ZEN), T-2, and HT-2 toxins. Although the concentrations are below the permissible limits, the presence of contaminants warrants regular monitoring, as they may have a cumulative effect on animal health [36], [125], [126]. Naibaho et al. [127] also found that compositional and structural diversity in BSG, specifically in the fibre matrix, may affect the product's quality characteristics and processing behaviour, thereby emphasising the importance of standardised quality control procedures. Given the regulations, the BSG used in animal feed must meet international safety standards for contaminants and feed hygiene, including mycotoxin, heavy metal, and microorganism levels in the product. This, in a way, puts the BSG in a different category, that of a product rather than a waste product, and calls for the implementation of regulations concerning the traceability of the product, hazard analysis, and the implementation of GMPs. Furthermore, the brewing process minimizes the microorganism hazard, and no major human pathogens are present in the BSG after the brewing process; however, that in no way implies that the product should not be handled after the brewing process since the risk of contaminants may be present [3]. In a study conducted by Chattaraj et al. [109] the incorporation of BSG in fish feed did not reveal any pathological effects and increased gut microbial diversity, indicating the biosafety of BSG under controlled conditions. This indicates the significant link between biological safety and the preceding quality management process. The valorisation of BSG in the feed system is not automatically safe and standardized but rather dependent on the implementation of effective quality control and contamination monitoring. In the absence of this, the technical transfer of waste to resource is precarious and emphasizes the fact that true valorisation of waste is

Table 8
Safety, quality & regulatory considerations for brewer's spent grain (BSG) use in animal feed.

Dimension	Key Issues/ Requirements	Rationale & implications	Example standards & regulations
Microbial safety	High spoilage risk due to moisture	BSG has 80% moisture, making it very perishable; without rapid processing or preservation, microbial growth (molds, thermophilic bacteria) degrades quality and increases the risk of pathogens and spoilage in feed. Poor storage leads to unpleasant odors, dry matter loss, and reduced palatability [128].	Preservation must minimize microbial proliferation; drying to $< 10\%$ moisture dramatically extends storage life [49].
Mycotoxin contamination	Natural toxin presence and monitoring	Cereal grains and byproducts (including BSG) are susceptible to fungal colonization; regulated mycotoxins such as zearalenone (ZEN), T-2 and HT-2 toxins can be present. Adequate monitoring is essential because these compounds can negatively affect animal health even at low levels [85].	EU and Codex frameworks set maximum mycotoxin levels for feed; regular testing and control strategies are part of safety compliance.
Chemical contaminants	Residues from farming inputs	Barley used in brewing may contain trace residues of pesticides or heavy metals that persist through brewing and end up in spent grain. While typical levels may be within limits, these contaminants require monitoring [36].	EU and Codex directives establish limits for pesticides, PCBs, dioxins, and heavy metals in feedstuffs. Compliance ensures both safety and market access [129].
Physical hazards	Foreign material & processing safety	During transport, handling, or storage, foreign objects such as metal or plastic or physical degradation can compromise feed safety and animal health. Strong quality control systems are therefore necessary [112].	Quality assurance best practices such as Good Manufacturing Practices (GMP) and HACCP help prevent physical hazards from entering feed streams.
Regulatory classification & compliance	Feed safety regulation frameworks	In major jurisdictions, animal feeds must be safe for target species and not compromise human food chains. Regulatory bodies such as the European Union and the U.S. FDA influence how BSG is tracked and verified when used in feeds [129].	Feed regulations require that the feed does not adversely affect animal or human health and limits undesirable substances [129].
Quality consistency	Variability in nutrient & contamination levels	BSG chemical composition and quality can vary by barley source, brewing process, and storage conditions. This variability complicates consistent feed formulation and must be addressed via routine analysis and quality assurance [49], [130].	Routine sampling and analytical testing (mycotoxins, heavy metals, moisture) are integral to quality control.

only possible when safety and quality are integrated in the process.

28. BSG-based industrial biorefineries and carbon cycling

Brewer's spent grain, abbreviated as BSG, is increasingly included in industrial biorefinery strategies that facilitate circular carbon utilisation. However, its valorisation is a combination of technological possibilities and systemic limitations. BSG is a lignocellulosic biomass that is rich in cellulose, hemicellulose, lignin, and proteins, thus offering a multi-fractional substrate that can be subjected to a series of conversion routes for producing fuels, chemicals, and biomaterials, thus matching the concept of integrated biorefining [22], [131], [132]. Current research has highlighted that integrated utilisation routes, such as those for extracting lipids, hydrolysing carbohydrates, and converting non-carbohydrates, ensure maximum utilisation efficiency, unlike single-product recovery strategies [133]. This is a shift from linear waste management to circular carbon cycling.

In carbon cycling, BSG is a renewable carbon pool that facilitates the conversion of organic carbon into biofuels, including bioethanol, biogas, and biodiesel. Integrated biorefineries that include anaerobic digestion, fermentation, and thermochemical conversion routes demonstrate that it is possible to generate several forms of energy from a single biomass, thus minimizing dependence on fossil fuels and mitigating environmental consequences [134]. According to Outeiriño et al. [135], the biorefinery strategy for the use of BSG has the potential to convert up to 80–85% of residues generated in the brewing process into value-added products. This indicates the significance of the biorefinery strategy in the sustainability of industrial processes. In addition to energy production, BSG is also being utilised in the development of more efficient biogenic carbon recycling strategies. This includes the microbial fermentation of BSG into platform chemicals, such as itaconate. This indicates the potential of agricultural residues in the development of the biochemical market [136]. According to Weiermüller et al. [137] BSG hydrolysates can be utilised as a viable carbon source in the development of microbial production systems. This indicates the importance of BSG in the development of the biochemical market.

Nevertheless, the industrialisation of BSG biorefinery systems is accompanied by significant techno-economic and scalability hurdles. Likewise, the moisture content and pre-treatment of the BSG may require significant operational and energy expenses, which may offset the overall environmental benefits [138], [139]. Additionally, while the development of novel strategies such as CO_2-assisted pyrolysis has shown the potential for the direct reduction of emissions and the utilization of CO_2 in the process of converting the BSG into energy and other products, the application of such strategies is only feasible in pilot-scale systems. This suggests that the carbon cycling benefits of such strategies are not fully realized [140], [141]. The biorefinery of BSG presents a real-world model of the circular economy of carbon. In the biorefinery of BSG, waste biomass is utilized in the production of energy and other products. However, sustainability is not only dependent on the development of new technologies but also on the optimization of the process and the overall economic and technological viability of the process in such a way that the carbon recovery strategies can be realized in terms of the overall reduction of the environmental footprint [142].

29. Concept of BSG biorefineries

BSG-based biorefineries represent a systems-based reconceptualisation of brewery waste products, in which spent grain is not merely viewed as waste but as a highly versatile carbon-based material within complex, multi-stage systems of valorisation. The conceptual basis for these biorefineries is underpinned by the biochemical composition of spent grain as a predominantly carbohydrate- and protein-based material with minor lipid-based moieties, which enables it to be targeted for partitioning into various bioconversion routes to ensure maximum efficiency in resource utilisation and carbon-based material efficiency. As Agrawal et al. [143] noted, the material's availability, low cost, and constant supply make spent grain a highly promising material for biorefineries; however, the material's underutilization is a function of systemic failure to effectively translate material composition into material value. The conceptual basis of the biorefinery-based approach to spent grain is the notion of cascading bioconversion, wherein various stages of material bioconversion are designed to ensure maximum utilisation of material composition before residual material is channelled into various forms of energy-based utilisation systems. The cascading logic is obviously important for carbon cycling within the biorefinery, as it extends carbon retention through multiple product lifecycle stages rather than allowing its rapid dissipation through disposal or low-grade utilisation routes. In this context, integrated configurations involving biochemical routes, e.g., enzymatic hydrolysis and fermentation, and thermochemical routes, e.g., anaerobic digestion and pyrolysis, are illustrative examples of how carbon retained within lignocellulosic matrices may be repeatedly converted into high-value product streams with minimised waste streams. Moraes dos Santos et al. [144] observed that integrated configurations of BSG biorefineries have been shown to increase efficiency and product portfolio, and to minimise the carbon footprint of brewery operations. Although this conceptual logic appears sound, actual industrial implementation of BSG biorefineries is hindered by a significant innovation–implementation gap, wherein Evaristo et al. [145] observed that although BSG biorefinery-related scientific literature is rapidly expanding, patenting and actual implementation are lagging, suggesting a lack of technological and/or economic competitiveness of most BSG biorefinery innovations. This disconnect, therefore, reveals an important limitation inherent in contemporary biorefinery discussions, in which technical feasibility is often prioritised at the expense of systemic viability. In addition, the physicochemical properties of BSG impose considerable constraints on the viability of the biorefinery concept, as its high moisture content, vulnerability to spoilage, and energy-intensive processing requirements are considerable drawbacks. According to Pabbathi et al. [146], these factors, as well as transportation inefficiencies, are considerable barriers to BSG adoption as a reliable industrial feedstock, thus necessitating decentralized, brewery-integrated biorefinery systems rather than centralized processing infrastructures, as was revealed by the economic analysis by Buffington [147], wherein it was demonstrated that conventional market structures are not as advantageous for BSG valorisation due to limitations within the supply chain.

From a technological perspective, the development of new BSG biorefineries demonstrates the potential for a circular economy of carbon utilization through a combination of microbial and enzymatic technologies. In a study, Outeiriño et al. [135] demonstrated that the production of biofuel intermediates from pretreated BSG and subsequent fermentation can produce large amounts of lactic acid and biosurfactants, thus providing a model for the retention of carbon within a controlled bioprocessing system. Significantly, the overall theoretical framework of BSG biorefineries can be enhanced by drawing parallels with other agricultural residues, such as spent coffee grounds, where integrated biorefineries have been demonstrated to offer a high techno-economic potential through diversification of products and synergy of process. Taifouris et al. [148] demonstrated that the systematic integration of multiple conversion pathways offers significant opportunities for increased profitability, suggesting that similar optimisation strategies can be adapted for BSG biorefineries to address economic limitations. To sum up, BSG-based industrial biorefineries embody a promising but underdeveloped bio-based economy paradigm defined by the potential to operationalize carbon cycling via cascading multi-product conversion systems. Nevertheless, the translation of BSG-based biorefineries from a conceptual framework into an industrial reality requires not only the improvement of existing technologies but also the reconfiguration of existing supply systems, economic models, and institutional relationships. Fig. 5 illustrates the integrated biorefinery pathway for converting brewer's spent grain (BSG) into

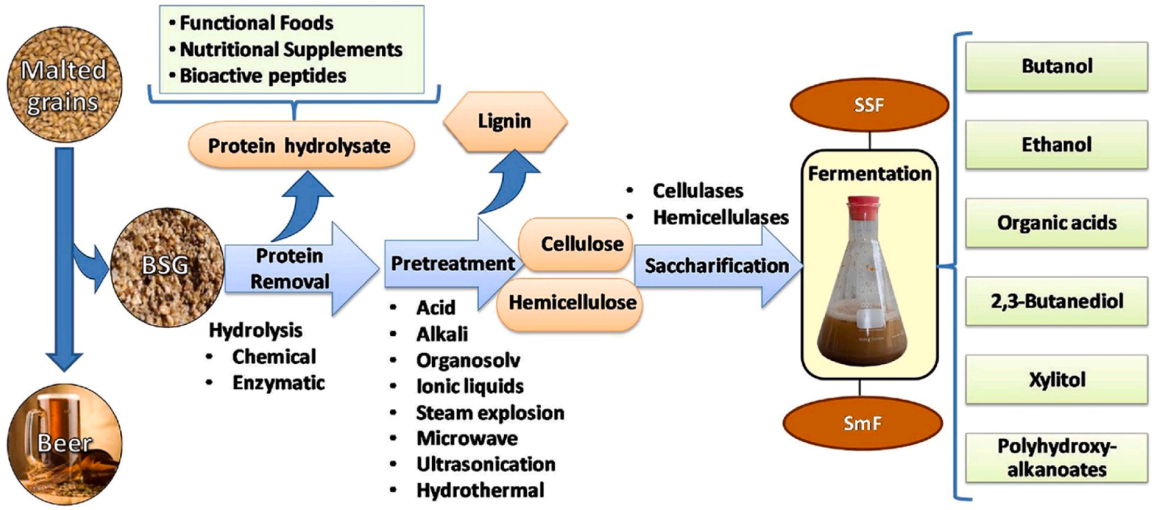

Fig. 5. Schematic representation of BSG valorisation showing protein recovery, lignocellulosic fractionation, and biochemical conversion into biofuels and biochemicals such as ethanol, butanol, organic acids, and biopolymers (adapted from Deepti Agrawal et al. [143]).

value-added products through sequential processes of protein extraction, pretreatment, saccharification, and fermentation.

30. Integration with brewery operations

The integration of brewer's spent grain (BSG) biorefineries into brewery processes marks a significant shift from the periphery of waste management to process intensification within a single framework of industrial metabolism. In a conceptual framework, this integration of BSG biorefineries into brewery processes changes the brewery from a linear production system to a circular biofactory where waste biomass is immediately redirected to valorisation pathways, thus reducing waste, energy loss, and greenhouse gas emissions. One of the characteristics of BSG biorefineries integration into brewery processes is the spatial and temporal proximity of BSG production and subsequent Valorisation. BSG is produced in large amounts, ranging from 17 to 45 kg per hectolitre of beer produced. In addition, BSG makes up to 85% of total solid waste from brewery processes.

Through the integration of biorefinery units directly into the brewery infrastructure, there is a significant reduction in the need for external transportation, storage, and stabilisation of the BSG (for example, drying), which is a critical aspect of biorefineries, considering the BSG's moisture content and biodegradability [144]. Hence, integration is not only beneficial but also a necessity from a functional perspective.

From a systems perspective, integrated BSG biorefineries would operate on the principle of process coupling, in which the brewing process is directly coupled to the bioconversion process. In this regard, BSG would be subjected directly to bioconversion processes such as pretreatment, hydrolysis, and fermentation, without the need for intermediate preservation strategies, thereby reducing overall process energy requirements. Such integrated biorefineries would also be a reflection of a new generation of bioprocess models where solid-state fermentation and enzymatic saccharification are conducted by harnessing the inherent potential of BSG, effectively internalising process inputs [135]. Such process models reflect industrial symbiosis at a micro-scale where waste streams are effectively converted into substrates for subsequent value-creation reactions. Most importantly, integration improves the efficiency of carbon cycling since carbon is retained within the brewery boundary. Rather than being considered a waste product or a low-value feedstock for production, the carbon content is progressively converted into biofuels, organic acids, biopolymers, or energy vectors at successive stages of processing. Integrated concepts such as anaerobic digestion, dark fermentation, and thermochemical conversion have been reported to achieve the highest level of material use, product diversification, and carbon footprint minimisation, thus creating a link with the concept of a circular bioeconomy [144]. In such a case, the brewery becomes a carbon processing unit where carbon footprint is reduced internally by recycling resources rather than treating waste externally.

However, it is important to note that the integration concept has some critical limitations. First off, the integration of existing breweries to accommodate a biorefinery concept demands a substantial capital investment. In addition to this, the composition of BSG also differs due to variations in the composition of raw materials used for fermentation and brewing, as well as the conditions of the brewing process and seasonal effects. These factors highlight the point that integration is not universally applicable but depends on various factors such as scale, technological maturity, and economic incentives [31]; [29]. In spite of these limitations, the development of new and evolving integrated concepts reveals the potential of breweries to be operated as decentralised biorefineries, specifically when implemented as greenfield or upgraded through the integration of various process units. The production of ethanol, biomass, and bioactive residues from a single source of BSG is an important example of the integration of biorefineries for the development of multiple revenue streams while ensuring the continuity of the process [149]. Such a strategy is critical to ensuring economic sustainability by diversifying risk through the development of diverse product portfolios.

30.1. Recycling of BSG within brewery operations

Beyond conversion into external food, feed, energy, and material products, BSG can also be recycled within brewery operations, creating a more closed-loop pathway for resource recovery. Jackowski et al. [150] demonstrated a dual-purpose torrefaction approach in which BSG was converted into a material with potential applications as both a solid fuel for brewery heat generation and a colouring agent for dark beer production. Mild torrefaction conditions (180 °C for 60 min and 210 °C for 40 min) produced European Brewery Convention colour values of 145 and 159, respectively, indicating the potential to replace conventional colouring malt in dark beer production. In contrast, more severe torrefaction conditions improved the fuel properties, with the higher heating value of torrefied BSG reaching 25 MJ/kg at 300 °C for 60 min. The study, therefore, highlighted a trade-off between optimising BSG for beer-colouring applications and maximising its solid-fuel properties [150].

More recently, direct reintegration of BSG with fresh malt has also been investigated as a route for returning spent grain-derived resources to the brewing process. Such approaches can enhance sugar release during mashing while reducing dependence on virgin malt and thereby strengthening material circularity within the brewery [151]. These examples demonstrate that BSG circularity can extend beyond downstream waste valorisation towards internal recycling within the brewing process itself. However, the practical implementation of such pathways requires consideration of torrefaction severity, beer colour and sensory quality, mash performance, food safety, and the balance between material recovery and energy generation [152]; [129].

31. Carbon recovery and reuse pathways

The emerging architecture of brewer's spent grain-based industrial biorefineries increasingly highlights the importance of carbon recovery and reuse schemes for carbon management. However, the existing literature reveals a highly disorganised and technologically uneven landscape. The most developed carbon management scheme is anaerobic digestion, in which carbon is recovered as a mixture of methane and recoverable CO_2. The empirical evidence reveals the carbon recovery potential of 82 m^3 CH_4 t^{-1} and 29 m^3 CO_2 t^{-1} , in which the recovered CO2 has the potential to reduce the costs of CO_2 procurement by the brewery sector by as much as 76% through its recycling [153]. However, the existing literature is mostly focused on the techno-economic optimisation of the carbon recovery schemes and is mostly focused on the energy recovery aspect, in which the potential of the CO_2 is not being utilised to the full.

Another pathway for carbon and energy recovery is the conversion of BSG into solid fuels for heat generation in breweries and biorefineries. The high moisture content of fresh BSG is a major limitation for direct fuel utilisation because it lowers energy density and increases the energy requirement for drying. Therefore, solid-fuel valorisation generally requires moisture reduction and, where appropriate, thermochemical upgrading. While dry BSG has been reported to exhibit calorific values of approximately 15.6–15.9 MJ/kg [29], an HHV of 18.74 MJ/kg has also been reported for brewery residues on a dry basis, whereas the corresponding LHV was 15.87 MJ/kg on an as-received basis [154]. Thermochemical processes such as hydrothermal carbonisation can further improve the fuel properties and energy density of BSG [155]. These values should be interpreted according to the corresponding moisture basis and heating-value definition, particularly the distinction between higher heating value (HHV) and lower heating value (LHV). Thermochemical processes such as hydrothermal carbonisation can further improve the fuel properties and energy density of BSG; for example, microwave-assisted hydrothermal carbonisation has produced BSG-derived hydrochar with calorific values of up to 32 MJ/kg [156]. Consequently, valorised BSG solid fuels could potentially be used to generate process heat within breweries or integrated biorefineries, thereby reducing dependence on external fossil-fuel inputs. However, the energy required for drying and thermochemical upgrading must be considered when assessing the net carbon and energy benefits of this pathway.

The more technologically advanced carbon management schemes, such as CO_2 -assisted pyrolysis, have the potential to develop a dual-loop carbon management scheme in which the CO_2 is not only recovered but also consumed in the process. Kim et al. [157] also demonstrated the potential for the simultaneous reduction of gaseous CO_2 emissions, along with the production of biochar, which has the capacity for further CO_2 adsorption, thus establishing the cascading carbon sink mechanism. Nevertheless, such processes are largely in the experimental phase, particularly in the validation of the process's energy balance in the context of carbon efficiency.

On the other hand, biochemical processes such as dark fermentation, along with integrated bioprocessing, have been established for the partial re-routing of carbon into hydrogen or intermediate products, though such processes often exhibit inefficient carbon usage, along with secondary emission issues. In the same vein, supercritical CO_2 (sc-CO_2) extraction provides an unconventional approach for the re-routing of CO_2, where it functions both as an extracting agent, while also enhancing the efficiency of downstream hydrolysis, thus achieving 5.7% lipid extraction, along with improved biomass accessibility. Though this approach provides the cyclical advantage, it does not entirely address the carbon re-routing challenge unless CO_2 recycling infrastructure is integrated [158], [159]. Importantly, there is a notable gap in the literature in terms of the development of integrated carbon cascade schemes to link the biological, thermochemical, and physicochemical carbon-based routes within a single optimized BSG biorefinery system. Rather, the literature is dominated by linear or single-process optimized routes without consideration of carbon leakage between these routes [160]. Additionally, there is a lack of quantification of the full carbon mass balance and emissions for these routes, making direct comparison of their relative sustainability challenging. Furthermore, there is a lack of investigation into high-value CO_2-based technologies, such as electrochemical reduction to fuels and chemicals within the context of the BSG biorefinery, which have been highlighted as having step-change potential in other industries [161].

32. Role in circular bioeconomy and low-carbon food systems

From a low-carbon food system perspective, the primary contribution of BSG is its substitution potential especially in animal feed and functional food ingredients where BSG acts as a substitute for conventional feedstocks such as soybean meal. This indirect path of carbon mitigation has significant structural effects, given the reduction in land-use emissions and transportation footprint. In addition, recent studies indicate that BSG has potential application as a fermentation feedstock for bio-based chemicals such as organic acids (e.g., itaconic acid), replacing petrochemical-based carbon streams with biogenic-based carbon streams [137]. Concurrently, recent innovations such as BSG-based bioplastics (e.g., the POLYMEER project) underscore BSG's potential in mitigating carbon-based materials, while global bioplastics production currently accounts for only 1.5% of total plastics production (POLYMEER project). Quantitative analyses of the environmental impact also underscore the potential of BSG-based carbon mitigation. In this case, studies indicate that BSG has significant potential to reduce greenhouse gas emissions from landfills (approximately 3 kg CO_2e/kg) by diverting the BSG feedstock to biochar production, with the resulting biochar potentially reducing emissions to 1.18 kg CO_2e/kg [162]. Such studies underscore BSG biorefineries' potential to serve as carbon retention systems. However, several gaps remain in the literature. Firstly, the majority of the literature has focused on the valorisation of BSG in isolation rather than as part of a comprehensive food-energy-material system. This has led to partial carbon cycling rather than the more desirable carbon cascading. Secondly, there is a bias in the literature towards the non-food sector, such as biofuels and materials, while the integration of BSG in low-carbon food systems, especially human nutrition, is not adequately explored [163]. This is mainly due to techno-functional and regulatory limitations. Thirdly, the literature has not adequately quantified the carbon displacement potential of food-energy-material systems [164]. In addition, there are logistical and geographical disconnects between breweries and downstream users that limit circularity and therefore maintain the use of low-value options such as animal feed, which, while beneficial, does not fully maximize the carbon value hierarchy. Finally, there is a disconnect between the theory of circular bioeconomies and their implementation in practice, with few large-scale BSG biorefineries operating as closed-loop, multi-output production systems [152]. Notwithstanding this, while BSG-based biorefineries have a strong alignment with theory in terms of circular bioeconomies and low-carbon food transitions, their current implementation is characterised by fragmented valorisation, a lack of integration, and a lack of carbon accounting frameworks, thereby limiting their decarbonisation potential.

33. Environmental, economic, and sustainability impacts

The environmental, economic, and sustainability aspects of industrial biorefineries utilising brewer's spent grain (BSG) have been extensively studied through life cycle assessment (LCA), carbon accounting, and techno-economic analyses. However, a thorough review of these studies highlights both clear advantages and ongoing structural challenges that limit their full potential in circular carbon systems.

34. Life cycle assessment (LCA) of BSG valorisation

LCA research consistently shows that valorising BSG is more environmentally favourable than disposal methods, though results vary greatly based on system boundaries, allocation methods, and technological setups. Transforming BSG into biochar can lower greenhouse gas (GHG) emissions from about 3 kg CO_2-eq per kg (landfilling) to 1.18 kg CO_2-eq per kg, indicating significant mitigation potential under controlled processing conditions. Similarly, the LCA of biochemical conversion pathways, such as microbial production of 2,3-butanediol (BDO), shows a global warming potential of 7.25 kg CO_2 per kg of product, with the pretreatment and fermentation stages being the main environmental burdens [162], [165]. Comparative LCA analyses further suggest that integrated platforms combining protein extraction and volatile fatty acid (VFA) production are more effective than single-product systems, emphasizing the importance of process integration in reducing overall impacts. However, critical gaps remain. First, most LCAs are cradle-to-gate, excluding downstream use-phase benefits and substitution effects, thus underestimating the true carbon displacement potential of BSG-derived products. Second, there is limited standardization in functional units (e.g., per kg BSG vs. per kg product), making cross-study comparisons unreliable. Third, many studies rely on laboratory or modelled data, which often fail to capture real industrial inefficiencies, particularly in drying and transport, which are repeatedly identified as dominant environmental hotspots [166].

35. 8.2 Carbon footprint reduction and climate benefits

BSG biorefineries aid climate mitigation through both direct and indirect carbon pathways. Direct reductions come from avoiding methane emissions associated with landfilling and replacing fossil-based products with biogenic alternatives. Indirect benefits arise from substitution effects, such as replacing soybean meal in feed or petrochemical intermediates in industrial processes. Diverting BSG to valorisation pathways rather than landfill can cut emissions by more than 60%, depending on the processing route. Additionally, integrated biorefineries that recover energy (e.g., via anaerobic digestion) can offset fossil fuel consumption, further enhancing carbon savings. Despite these benefits, the literature shows a systematic underestimation of carbon leakage across supply chains. High moisture content requires energy-intensive drying, which can negate climate benefits if powered by fossil energy. Moreover, transportation distances between breweries and biorefineries significantly affect net emissions, yet are often considered secondary parameters [162]. Moreover, studies reveal that not all valorisation routes are inherently low-carbon; combustion-based energy recovery from BSG can result in relatively high emissions due to the energy demands of preprocessing. Thus, assuming all BSG valorisation is climate-positive is overly simplistic and requires context-specific validation [167].

36. 8.3 Techno-economic feasibility

In techno-economic assessments of BSG biorefineries, there is a complex interplay between environmental impacts and economic viability. High-value biochemical-based routes, such as the fermentation of BDO, have been proven to be technically viable on an industrial scale, with the ability to process 100 metric tons of BSG per day [165]. However, these routes are hindered by high capital and operating costs due to pretreatment and purification steps. On the other hand, simpler routes such as animal feed, are still economically viable due to low processing costs, with 70% of the total amount of BSG currently utilised for this purpose [128]. However, one of the major drawbacks of TEA studies is the lack of consideration of co-products and carbon pricing strategies, which may significantly impact the economic evaluation of BSG biorefineries. Again, scaling up is a major challenge due to feedstock costs and seasonality. Additionally, the perishability of BSG is only for 3–5 days without preservation; therefore, there are additional costs for storage and preservation of the feedstock [128].

37. Contribution to sustainable development goals (SDGs)

It is theoretically possible for BSG-based biorefineries to contribute to achieving several Sustainable Development Goals, specifically 12 (Responsible Consumption and Production), 13 (Climate Action), and 7 (Affordable and Clean Energy). The use of a substantial quantity of agro-industrial residues, estimated at 36.4 million metric tons per year, for the production of valuable chemicals, fuels, and other commodities contributes significantly to the achievement of the Sustainable Development Goals related to food waste reduction. In addition, the energy production pathways contribute to renewable energy generation, while the material and biochemical pathways contribute to the transition to a bio-based economy [162]. Nevertheless, the contribution of BSG biorefineries to the Sustainable Development Goals is only partially achieved. First, the dominance of low-value products, such as animal feed, limits the potential for achieving higher-order circularity and economic growth. Second, there is a lack of quantitative frameworks for the Sustainable Development Goals, as most existing studies are qualitative. Thirdly, there are no significant studies on the social and regional issues associated with biorefineries, such as the impact on rural livelihoods and supply chain equity. There is a disconnect between the global sustainability picture and regional implementation realities.

From an environmental, economic, and sustainability perspective, BSG-based biorefineries offer promise but are constrained by systemic fragmentation. There are significant gaps that need to be filled from an integrated perspective. Firstly, there are no integrated assessment tools that can simultaneously assess environmental sustainability, economic viability, and social sustainability. Existing studies are fragmented and focus on either LCA or TEA but not a combination of the two. Secondly, there is a significant need for industrial-scale validation of existing laboratory-scale studies. Specifically, there is a need for data on energy consumption, emissions, and efficiency. Finally, there is a need for systemic changes from a linear to a circular economy. Such changes require not only technological innovation but also institutional and infrastructural changes to support policies that promote the reuse of carbon dioxide. Therefore, while BSG valorisation pathways offer measurable environmental benefits and align conceptually with circular bioeconomy and sustainability goals, their current implementation is limited by methodological inconsistencies, economic uncertainties, and incomplete system integration, underscoring the need for more holistic and scalable research approaches.

38. Challenges, innovations, and future perspectives

Brewer’s spent grain-based industrial biorefineries are a promising option for the development of circular bioeconomy schemes; however, various hurdles need to be addressed along the technological, regulatory, and commercialisation aspects. From a technological point of view, the major challenge is the feedstock's properties and scaling up the process. Brewer’s spent grain contains 70–80% moisture and is highly perishable and expensive to transport or store without pretreatment [15]. This leads to the need for costly and energetically demanding drying or direct processing of the material, which is not industrially attractive. Furthermore, the inherent lignocellulosic nature of spent grain requires additional pretreatment steps, which are costly and time-consuming. Although various laboratory-scale studies have reported successful conversions to biofuels, enzymes, and biomaterials, only a small number of applications exist at the industrial scale, indicating a need to bridge the gap between successful laboratory-scale trials and commercial-scale applications [146]. Comparative analyses have also been conducted to highlight the technological readiness of various routes for spent grain-based biorefineries; whereas AD and pyrolysis are well-established routes, emerging routes such as dark fermentation require substantial investment and optimisation for successful commercialisation [144]. There is another level of complexity in the food and animal feed safety regulations. The BSG is widely used as animal feed, but its high moisture content and microbial activity render it prone to spoilage and potential contamination within a few days. Most importantly, there is a potential risk of mycotoxins and microbial hazards, which require stringent monitoring and processing [168], [169]. The regulations governing the use of BSG in the human food system are inconsistent across countries, creating a major gap for the industrial community. The lack of consistency in safety validation protocols and quality standards across the globe has not yet been resolved, creating confusion for the industrial community. Despite the challenges, the recent industrial innovations offer promising opportunities. The biorefinery concept, which combines the production of bio-energy, food--grade ingredients, and biochemicals, is gaining momentum [128].

Process integration in breweries, such as the integration of anaerobic digestion and subsequent energy production, also shows promise for reducing carbon footprints and costs at the same time [3]. Yet, as is also the case for other areas of innovation, most of the advances in the field have been reported at the pilot scale and not at the fully functional and operational industrial scale [170]. In terms of looking into the future of the field and the key areas of improvement and development for the biorefineries based on BSG and brewery waste, several key areas of improvement and development need to be addressed and resolved in the near future to ensure the full potential of biorefineries for the advancement of carbon cycling is realized and not only partially addressed as is currently the case without these key areas of improvement and development being addressed and resolved.

39. Conclusion

Brewer's spent grains are among the most abundant agro-industrial residues worldwide and have substantial potential as a carbon-rich feedstock for producing food, feed, and biorefining products. This review article has shown that the lignocellulosic composition, protein content, dietary fibre, and bioactive compounds of BSG have substantial potential for use in food, feed, and biorefinery products. However, despite the substantial potential of BSG for large-scale use, it is limited by factors such as high moisture content, variability in BSG composition, processing costs, legal limitations, and lack of biorefining facilities. The review also highlights that future BSG utilisation will involve a shift towards "integrated cascading biorefineries that maximise carbon retention, resource efficiency, and value-added aspects." In addition, improvements in process integration in breweries, decentralised process systems, and carbon accounting systems will be important for unlocking the environmental and economic potential of BSG valorisation. Overall, it will be important to unlock the value of BSG by shifting from low-value uses, such as animal feed, to high-value food, feed, and bio-products, positioning brewer's spent grains as a key resource in the bioeconomy.

CRediT authorship contribution statement

Lukman Shehu Mustapha: Writing – original draft, Visualization, Conceptualization. **Kehinde Shola Obayomi:** Writing – review & editing, Conceptualization. **Oluwatobi Victoria Obayomi:** Writing – original draft, Visualization, Conceptualization. **Baba IsaacAlhamdu:** Writing – original draft, Visualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

[1] M. Lech, K. Labus, The methods of brewers' spent grain treatment towards the recovery of valuable ingredients contained therein and comprehensive management of its residues, Chem. Eng. Res. Des. 183 (2022) 494–511, https://doi.org/10.1016/j.cherd.2022.05.032.
[2] S.I. Mussatto, G. Dragone, I.C. Roberto, Brewers' spent grain: generation, characteristics and potential applications, J. Cereal Sci. 43 (1) (2006) 1–14, https://doi.org/10.1016/j.jcs.2005.06.001.
[3] A. Bianco, M. Budroni, S. Zara, I. Mannazzu, F. Fancello, G. Zara, The role of microorganisms on biotransformation of brewers' spent grain, Appl. Microbiol. Biotechnol. 104 (20) (2020) 8661–8678, https://doi.org/10.1007/s00253-020-10843-1.
[4] K.K. Beltrán-Borbor, A.D. Ortega-Suasnavas, M.V. Ordóñez-Pazmiño, D.L. Tinoco-Caicedo, Utilization of brewer's spent grain in extrusion processing: A review, Appl. Food Res. 5 (1) (2025) 100868, https://doi.org/10.1016/j.afres.2025.100868.
[5] L. Nyhan, A.W. Sahin, H.H. Schmitz, J.B. Siegel, E.K. Arendt, Brewers' Spent Grain: An Unprecedented Opportunity to Develop Sustainable Plant-Based Nutrition Ingredients Addressing Global Malnutrition Challenges, J. Agric. Food Chem. 71 (28) (Jul. 2023) 10543–10564, https://doi.org/10.1021/acs.jafc.3c02489.
[6] Y. Zheng, et al., Influence of moisture content on microbial activity and silage quality during ensilage of food processing residues, Bioprocess. Biosyst. Eng. 34 (May 2011) 987–995, https://doi.org/10.1007/s00449-011-0549-4.
[7] Y. Liu, et al., Effects of Moisture Content Gradient on Alfalfa Silage Quality, Odor, and Bacterial Community Revealed by Electronic Nose and GC–MS, Microorganisms 13 (2) (2025) 1–21, https://doi.org/10.3390/microorganisms13020381.
[8] S. Villacreces, C.A. Blanco, I. Caballero, Developments and characteristics of craft beer production processes, Food Biosci. 45 (2022) 101495, https://doi.org/10.1016/j.fbio.2021.101495.
[9] L.S. Mustapha, I.S. Tan, J.S.Y. Lau, H.C.Y. Foo, J. Kansedo, M.K. Lam, Algal cellulose and its nanoscale derivatives for sustainable polymer nanocomposites, Discov. Appl. Sci. (2026), https://doi.org/10.1007/s42452-026-09035-9.
[10] L.O. da Silva, F.M.S. Silva, J.P. Bassin, Brewery Byproducts as Bioenergy Sources: A Review of Biohydrogen and Biomethane Production, no. 0123456789, Waste Biomass-.-. Valoriz. (2026), https://doi.org/10.1007/s12649-026-03515-0.
[11] D. Alp, Ö. Bulantekin, The microbiological quality of various foods dried by applying different drying methods: a review, Eur. Food Res. Technol. = Z. fur Leb. und -Forsch. A 247 (6) (2021) 1333–1343, https://doi.org/10.1007/s00217-021-03731-z.
[12] L. Fillaudeau, A. Bories, M. Decloux, Brewing, winemaking and distilling: an overview of wastewater treatment and utilisation schemes, Woodhead Publ. Ser. Food Sci. Technol. Nutr. J. Klemeš R. Smith J. -K. B. T. -H. W. E. M. F. P. Kim. Eds. Woodhead Publ. 35 (2008) 929–995, https://doi.org/10.1533/9781845694678.6.929.
[13] D. Díez, A. Urueña, R. Piñero, A. Barrio, T. Tamminen, and Lignin Content in Di ff erent Types of Biomasses by Thermogravimetric Analysis and Pseudocomponent Kinetic Model,", Processes 8 (1048) (2020) 1–21.
[14] S. Lv, et al., The Influence of Hemicellulose and Lignin Removal on the Enzymatic Digestibility from Sugarcane Bagasse, BioEnergy Res. 6 (Dec. 2013), https://doi.org/10.1007/s12155-013-9297-4.
[15] J. Henkin, K. Mainali, B. Sharma, H. Ngo, M. Sarker, A Review of Chemical and Physical Analysis, Processing, and Repurposing of Brewers' Spent Grain, Biomass 5 (Jul. 2025) 42, https://doi.org/10.3390/biomass5030042.
[16] S.M.N.K. Zihad, et al., Nutritional value, micronutrient and antioxidant capacity of some green leafy vegetables commonly used by southern coastal people of Bangladesh, Heliyon 5 (11) (2019) e02768, https://doi.org/10.1016/j.heliyon.2019.e02768.
[17] V. Gressler, et al., Lipid, fatty acid, protein, amino acid and ash contents in four Brazilian red algae species, Food Chem. 120 (2) (2010) 585–590, https://doi.org/10.1016/j.foodchem.2009.10.028.
[18] A. Marcus, G. Fox, Fungal Biovalorization of a Brewing Industry Byproduct, Brewer's Spent Grain: A Review, Foods (Basel Switz.) 10 (9) (Sep. 2021), https://doi.org/10.3390/foods10092159.

[19] M.A. Aborisade, et al., Bio-Based Fertilizers from Waste: Nutrient Recovery, Soil Health, and Circular Economy Impacts, Toxics 14 (1) (2026) 90, https://doi.org/10.3390/toxics14010090.

[20] E.M. Gonçalves, J.M. Pestana, N. Alvarenga, Fermenting the Unused: Microbial Biotransformation of Food Industry By-Products for Circular Bioeconomy Valorisation, Fermentation 12 (2) (2026) 1–32, https://doi.org/10.3390/fermentation12020073.

[21] A. Dadrasnia, et al., Sustainable nutrient recovery from animal manure: A review of current best practice technology and the potential for freeze concentration, J. Clean. Prod. 315 (Jun. 2021) 128106, https://doi.org/10.1016/j.jclepro.2021.128106.

[22] T. Kalak, Characterization and Sustainable Valorization of Brewers' Spent Grain for Metal Ion and Organic Substance Removal, Sustain 17 (20) (2025) 1–37, https://doi.org/10.3390/su17209288.

[23] N. Lojananan, et al., Successive process for efficient biovalorization of Brewers' spent grain to lignocellulolytic enzymes and lactic acid production through simultaneous saccharification and fermentation, Bioresour. Technol. 397 (2024) 130490, https://doi.org/10.1016/j.biortech.2024.130490.

[24] J. Zhang, A. Perez-Gavilan, A. Cunha Neves, Optimization of Solid-State Fermentation Conditions With Mixed Strains Using Box-Behnken Design for the Production of brewers' Spent Grain Protein, J. Am. Soc. Brew. Chem. 82 (4) (2024) 468–479, https://doi.org/10.1080/03610470.2024.2325748.

[25] J. Naibaho, M. Korzeniowska, A. Wojdyło, H. Muchdatul Ayunda, M. Foste, B. Yang, Techno-functional properties of protein from protease-treated brewers' spent grain (BSG) and investigation of antioxidant activity of extracted proteins and BSG residues, J. Cereal Sci. 107 (2022) 103524, https://doi.org/10.1016/j.jcs.2022.103524.

[26] Z. Qazanfarzadeh, A. Masek, S. Chakraborty, V. Kumaravel, Development of brewer's spent grain-derived bio nanocomposites through a multiproduct biorefinery approach for food packaging, Ind. Crops Prod. 220 (2024) 119226, https://doi.org/10.1016/j.indcrop.2024.119226.

[27] M.A. Farooq, J. Yu, Recent Advances in Physical Processing Techniques to Enhance the Resistant Starch Content in Foods: A Review, Foods (Basel Switz.) 13 (17) (Aug. 2024), https://doi.org/10.3390/foods13172770.

[28] H. Tong, et al., Extraction Techniques for Brewer's Spent Grain Protein: A Comparative Review of Efficiency, Purity, and Functionality, Foods (Basel Switz.) 14 (23) (Nov. 2025), https://doi.org/10.3390/foods14234058.

[29] O.V. Obayomi, J.T. Alabi, L.S. Mustapha, E.V. Ayodawha, K.S. Obayomi, Recent advances in valorization pathways for food manufacturing waste, Sustain. Chem. One World 10 (2026) 100243, https://doi.org/10.1016/j.scowo.2026.100243.

[30] Y. He, J.A. OHair, Q. Jin, Z. Xu, J. Wu, H. Huang, Co-Production of Protein Hydrolysates and 2,3-Butanediol from Brewer's Spent Grain, ACS Sustain. Chem. Eng. 9 (45) (Nov. 2021) 15166–15174, https://doi.org/10.1021/acssuschemeng.1c04162.

[31] A. Zeko-Pivač, et al., The Potential of Brewer's Spent Grain in the Circular Bioeconomy: State of the Art and Future Perspectives (no. June), Front. Bioeng. Biotechnol. 10 (2022) 1–15, https://doi.org/10.3389/fbioe.2022.870744.

[32] S. Głowacki, et al., The Use of Brewer's Spent Grain after Beer Production for Energy Purposes, Mater. (Basel Switz. 15 (10) (May 2022), https://doi.org/10.3390/ma15103703.

[33] K. Rachwał, A. Waśko, K. Gustaw, M. Polak-Berecka, Utilization of brewery wastes in food industry, PeerJ 8 (2020) e9427, https://doi.org/10.7717/peerj.9427.

[34] E.B. Özvural, H. Vural, İ. Gökbulut, Ö. Özboy-Özbaş, Utilization of brewer's spent grain in the production of Frankfurters, Int. J. Food Sci. Technol. 44 (6) (Jun. 2009) 1093–1099, https://doi.org/10.1111/j.1365-2621.2009.01921.x.

[35] T. Mulu, et al., Valorisation of brewery spent grain for biogas production and nutrient-enriched bioslurry in sustainable agriculture, Int. J. Sustain. Energy 45 (1) (Dec. 2026) 2629665, https://doi.org/10.1080/14786451.2026.2629665.

[36] V. Eche, C.U. Emenike, H.P.V. Rupasinghe, Nutritional Value of Brewer's Spent Grain and Consumer Acceptance of Its Value-Added Food Products, Foods 14 (16) (2025) 1–27, https://doi.org/10.3390/foods14162900.

[37] J. Naibaho, M. Korzeniowska, The variability of physico-chemical properties of brewery spent grain from 8 different breweries, Heliyon 7 (3) (2021) e06583, https://doi.org/10.1016/j.heliyon.2021.e06583.

[38] M. Santos, J.J. Jiménez, B. Bartolomé, C. Gómez-Cordovés, M.J. del Nozal, Variability of brewer's spent grain within a brewery, Food Chem. 80 (1) (2003) 17–21, https://doi.org/10.1016/S0308-8146(02)00229-7.

[39] A.E. Universa, A. Banis, T. Kince, Z. Kruma, I. Dabina-Bicka, Nutritional Characterization of Brewer's Spent Grains Depending on Brewery Scale and Beer Production Technology, Foods (Basel Switz.) 14 (23) (Nov. 2025), https://doi.org/10.3390/foods14234052.

[40] Analysis of the Physico-chemical Characteristics of Brewers Spent Grain (BSG), Y. K. Gebreyes 11 (Jan. 2020) 8–12, https://doi.org/10.7176/JNSR/11-18-02.

[41] S. Wilkinson, K.A. Smart, S. James, D.J. Cook, Bioethanol Production from Brewers Spent Grains Using a Fungal Consolidated Bioprocessing (CBP) Approach, Bioenergy Res. 10 (1) (2017) 146–157, https://doi.org/10.1007/s12155-016-9782-7.

[42] K. Vanreppelen, S. Vanderheyden, T. Kuppens, S. Schreurs, J. Yperman, R. Carleer, Activated carbon from pyrolysis of brewer's spent grain: Production and adsorption properties, Waste Manag. Res. J. Int. Solid. Wastes Public. Clean. Assoc. ISWA 32 (7) (Jul. 2014) 634–645, https://doi.org/10.1177/0734242X14538306.

[43] A. Jaeger, E. Zannini, A.W. Sahin, E.K. Arendt, Barley protein properties, extraction and applications, with a focus on brewers' spent grain protein, Foods 10 (6) (2021) 1–21, https://doi.org/10.3390/foods10061389.

[44] P. Aradwad, S. Raut, A. Abdelfattah, C. Rauh, B. Sturm, Brewer's spent grain: Unveiling innovative applications in the food and packaging industry, Compr. Rev. Food Sci. Food Saf. 24 (3) (May 2025) e70150, https://doi.org/10.1111/1541-4337.70150.

[45] K. Lynch, E. Steffen, E. Arendt, Brewers' spent grain: A review with an emphasis on food and health, J. Inst. Brew. 122 (Oct. 2016), https://doi.org/10.1002/jib.363.

[46] S. Sobek, K. Zeng, S. Werle, R. Junga, M. Sajdak, Brewer's spent grain pyrolysis kinetics and evolved gas analysis for the sustainable phenolic compounds and fatty acids recovery potential (no. July), Renew. Energy 199 (2022) 157–168, https://doi.org/10.1016/j.renene.2022.08.114.

[47] P. Niemi, et al., Characterization of Lipids and Lignans in Brewer's Spent Grain and Its Enzymatically Extracted Fraction, J. Agric. Food Chem. 60 (39) (Oct. 2012) 9910–9917, https://doi.org/10.1021/jf302684x.

[48] M. Ummels, L. JanssenDuijghuijsen, J.J. Mes, C. van der Aa, R. Wehrens, D. Esser, Evaluating Brewers' Spent Grain Protein Isolate Postprandial Amino Acid Uptake Kinetics: A Randomized, Cross-Over, Double-Blind Controlled Study, Nutrients 15 (14) (Jul. 2023), https://doi.org/10.3390/nu15143196.

[49] A. Chetrariu, A. Dabija, Brewer's spent grains: Possibilities of valorization, a review, Appl. Sci. 10 (16) (2020) 1–17, https://doi.org/10.3390/app10165619.

[50] R.I. Birsan, P. Wilde, K.W. Waldron, D.K. Rai, Recovery of Polyphenols from Brewer's Spent Grains, Antioxid. (Basel Switz.) 8 (9) (Sep. 2019), https://doi.org/10.3390/antiox8090380.

[51] M. Verni, et al., Bioprocessing of Brewers' Spent Grain Enhances Its Antioxidant Activity: Characterization of Phenolic Compounds and Bioactive Peptides, Front. Microbiol. 11 (2020) 1831, https://doi.org/10.3389/fmicb.2020.01831.

[52] S.I. Mussatto, M. Fernandes, G.J.M. Rocha, J.J.M. Orfão, J.A. Teixeira, I. C. Roberto, Production, characterization and application of activated carbon from brewer's spent grain lignin, Bioresour. Technol. 101 (7) (Apr. 2010) 2450–2457, https://doi.org/10.1016/j.biortech.2009.11.025.

[53] S. Raviolo, et al., Valorization of brewer's spent grain via systematic study of KOH activation parameters and its potential application in energy storage, Biomass-.-. Bioenergy 192 (2025) 107494, https://doi.org/10.1016/j.biombioe.2024.107494.

[54] S. Pérocheau Arnaud, Valorisation of Brewer's Spent Grain: Lignocellulosic Fractionation and its Potential for Polymer and Composite Material Applications, Chem. Afr. 7 (6) (2024) 2989–3010, https://doi.org/10.1007/s42250-024-00966-7.

[55] T.P. de Araújo, H.B. Quesada, R. Bergamasco, D.T. Vareschini, M.A.S.D. de Barros, Activated hydrochar produced from brewer's spent grain and its application in the removal of acetaminophen, Bioresour. Technol. 310 (Aug. 2020) 123399, https://doi.org/10.1016/j.biortech.2020.123399.

[56] S. Riaz, A.J. John, M.S. Samuel, S. Ethiraj, Recent developments and emerging methodologies in the pre-treatment of lignocellulosic biomass, Sustain. Chem. Environ. 11 (2025) 100285, https://doi.org/10.1016/j.scenv.2025.100285.

[57] V. Ahuja, S. Chauhan, Y.-H. Yang, S.K. Bhatia, V. Kumar, From Brew to Table: Unleashing the potential of spent grains protein, J. Cereal Sci. 117 (2024) 103896, https://doi.org/10.1016/j.jcs.2024.103896.

[58] M.V. Santos, N. Ranalli, J. Orjuela-Palacio, N. Zaritzky, Brewers spent grain drying: Drying kinetics, moisture sorption isotherms, bioactive compounds stability and Bacillus cereus lethality during thermal treatment, J. Food Eng. 364 (2024) 111796, https://doi.org/10.1016/j.jfoodeng.2023.111796.

[59] M. Gallego-García, A.D. Moreno, P. Manzanares, M.J. Negro, A. Duque, Recent advances on physical technologies for the pretreatment of food waste and lignocellulosic residues, Bioresour. Technol. 369 (2023) 128397, https://doi.org/10.1016/j.biortech.2022.128397.

[60] R. Ravindran, et al., Improving enzymatic hydrolysis of brewer spent grain with nonthermal plasma, Bioresour. Technol. 282 (Mar. 2019), https://doi.org/10.1016/j.biortech.2019.03.071.

[61] J.A. Rojas-Chamorro, J.M. Romero-García, C. Cara, I. Romero, E. Castro, Improved ethanol production from the slurry of pretreated brewers' spent grain through different co-fermentation strategies, Bioresour. Technol. 296 (2020) 122367, https://doi.org/10.1016/j.biortech.2019.122367.

[62] P.E. Plaza, M. Coca, S. Lucas, M. Fernández-Delgado, J.C. López-Linares, M. T. García-Cubero, Efficient use of brewer's spent grain hydrolysates in ABE fermentation by Clostridium beijerinkii. Effect of high solid loads in the enzymatic hydrolysis, J. Chem. Technol. Biotechnol. 95 (9) (Sep. 2020) 2393–2402, https://doi.org/10.1002/jctb.6421.

[63] H. Peng, et al., Production of ethanol, butanol, itaconic acid, 3-hydroxypropionic acid, polyhydroxyalkanoates, and lignin from lignocellulosic biomass, Green. Chem. 27 (43) (2025) 13682–13691, https://doi.org/10.1039/d5gc04325e.

[64] V. Lourens, C.E. Bosman, A.M. Petersen, G. Coetzee, J.F. Görgens, E. van Rensburg, Simultaneous enzymatic hydrolysis and bioconversion of deacetylated and disk refined sugarcane bagasse to single-cell protein: An experimental investigation and techno-economic analysis, Biochem. Eng. J. 218 (2025) 109691, https://doi.org/10.1016/j.bej.2025.109691.

[65] T. Bonifácio-Lopes, L.M.G. Castro, A. Vilas-Boas, D. Campos, J.A. Teixeira, M. Pintado, Impact of gastrointestinal digestion simulation on brewer's spent grain green extracts and their prebiotic activity, Food Res. Int. 165 (Mar. 2023) 112515, https://doi.org/10.1016/j.foodres.2023.112515.

[66] M.H. Junttila, Extraction of brewers' spent grain in near subcritical conditions: A method to obtain high protein contents extracts, J. Agric. Food Res. 10 (2022) 100378, https://doi.org/10.1016/j.jafr.2022.100378.

[67] S. Lisci, et al., Valorizing brewer's spent grain: A sequential pathway of supercritical extraction, hydrolysis, and fermentation, Chem. Eng. Sci. 285 (2024) 119620, https://doi.org/10.1016/j.ces.2023.119620.

[68] M. Jayakumar, S. Kuppusamy Vaithilingam, N. Karmegam, K.B. Gebeyehu, M.S. Boobalan, and B. Gurunathan, "Chapter 6 - Fermentation technology for ethanol production: Current trends and challenges," B. Gurunathan and R. B. T.-B. and B. Sahadevan, Eds., Elsevier, 2022, pp. 105–131. doi:https://doi.org/10.1016/B978-0-323-90040-9.00015-1.
[69] R. Dharma Patria, et al., Bioconversion of food and lignocellulosic wastes employing sugar platform: A review of enzymatic hydrolysis and kinetics, Bioresour. Technol. 352 (2022) 127083, https://doi.org/10.1016/j.biortech.2022.127083.
[70] Y.L. Chin, J.K. Keppler, S.T. Dinani, W.N. Chen, R. Boom, Brewers' spent grain proteins: The extraction method determines the functional properties, Innov. Food Sci. Emerg. Technol. 94 (2024) 103666, https://doi.org/10.1016/j.ifset.2024.103666.
[71] Z. Maache-Rezzoug, T. Maugard, R. Goude, A. Nouviaire, F. Sannier, and S.-A. Rezzoug, "A THERMOMECHANICAL PROCESS FOR IMPROVING ENZYMATIC HYDROLYSIS OF BREWER'S SPENT GRAIN," Aug. 2008.
[72] G. Semaan, S.J. Klausen, C. Martín, K.B. Jørgensen, G. Kumar, Fractionation and characterization of multi-feedstock lignocellulosic biomass via two-stage pretreatment, Biomass-.-. Convers. Biorefinery 15 (12) (2025) 18925–18945, https://doi.org/10.1007/s13399-025-06576-8.
[73] J.A. Rojas-Chamorro, et al., Ethanol Production from Brewers' Spent Grain Pretreated by Dilute Phosphoric Acid, Energy & Fuels 32 (4) (Apr. 2018) 5226–5233, https://doi.org/10.1021/acs.energyfuels.8b00343.
[74] J.A. Rojas-chamorro, I. Romero, E. Ruiz, C. Cara, "Comp. Ferment. Strateg. Ethanol Prod. Pretre Brew. Spent Grain" 61 (2017) 637–642, https://doi.org/10.3303/CET1761104.
[75] S. Giacobbe, et al., Butanol production from laccase-pretreated brewer's spent grain, Biotechnol. Biofuels 12 (2019) 47, https://doi.org/10.1186/s13068-019-1383-1.
[76] R. Liguori, C.R. Soccol, L. Porto, D.S. Vandenberghe, A.L. Woiciechowski, V. Faraco, Second. Gener. Ethanol Prod. Brew. ' Spent Grain (2015) 2575–2586, https://doi.org/10.3390/en8042575.
[77] M.A. Manan, C. Webb, Mod. Microb. Solid. State Ferment. Technol. Future biorefineries Prod. added-Value Prod. 16 (2017) 730–740, https://doi.org/10.18331/BRJ2017.4.4.5.
[78] S.M. Safwa, T. Ahmed, S. Talukder, A. Sarkar, M.R. Rana, Applications of non-thermal technologies in food processing Industries-A review, J. Agric. Food Res. 18 (2024) 100917, https://doi.org/10.1016/j.jafr.2023.100917.
[79] P. Bucci, D. Cantero, A. Casas, E. Marcos, E. Menalla, R. Muñoz, Hydrothermal pretreatment of brewer's spent grain: A pathway to sustainable biogas production and waste valorization, Biomass-.-. Bioenergy 204 (2026) 108399, https://doi.org/10.1016/j.biombioe.2025.108399.
[80] J.C. López-Linares, M.T. García-Cubero, S. Lucas, G. González-Benito, M. Coca, Microwave assisted hydrothermal as greener pretreatment of brewer's spent grains for biobutanol production, Chem. Eng. J. 368 (2019) 1045–1055, https://doi.org/10.1016/j.cej.2019.03.032.
[81] R. Ravindran, S. Jaiswal, N. Abu-Ghannam, A.K. Jaiswal, A comparative analysis of pretreatment strategies on the properties and hydrolysis of brewers' spent grain, Bioresour. Technol. 248 (2018) 272–279, https://doi.org/10.1016/j.biortech.2017.06.039.
[82] L.S. Buller, W.G. Sganzerla, M.N. Lima, K.E. Muenchow, M.T. Timko, T. Forster-Carneiro, Ultrasonic pretreatment of brewers' spent grains for anaerobic digestion: Biogas production for a sustainable industrial development, J. Clean. Prod. 355 (2022) 131802, https://doi.org/10.1016/j.jclepro.2022.131802.
[83] K. Krochmalny *et al.*, "Use of Hydrothermal Carbonization and Cold Atmospheric Plasma for Surface Modification of Brewer ' s Spent Grain and Activated Carbon," 2022.
[84] A.S. Virdi, A. Mahajan, M. Devraj, R. Sanghi, Brewers' spent grains: Techno-functional challenges and opportunity in the valorization for food products, LWT 227 (2025) 117785, https://doi.org/10.1016/j.lwt.2025.117785.
[85] V. Eche, C.U. Emenike, H.P.V. Rupasinghe, Nutritional Value of Brewer's Spent Grain and Consumer Acceptance of Its Value-Added Food Products, Foods (Basel Switz.) 14 (16) (Aug. 2025), https://doi.org/10.3390/foods14162900.
[86] M.A. Ribeiro-Sanches, V.A.L. Stochi, A.L. Borges-Machado, P.E.D. Augusto, T. C. Polachini, J. Telis-Romero, Valorization of brewer's spent grains (BSG) through alkaline hydrogen peroxide processing: Effect on composition, structure and rheological properties, Food Bioprod. Process. 147 (2024) 239–250, https://doi.org/10.1016/j.fbp.2024.07.008.
[87] H. Saberian, A. Pouya, G. Yazdi, M. Nejatian, Brewers ' spent grain as a functional ingredient in bakery, pasta, and cereal-based products (no. July, p), Futur. Foods 10 (2024) 100479, https://doi.org/10.1016/j.fufo.2024.100479.
[88] N. Lorena, E. Wagner, M. Eugenia, D. Ghiringhelli, Ind. Crops & Prod. Valoriz. Brew. ' S. spent grain Differ. Strateg. Struct. destabilization Enzym. Saccharif. 163 (2021), https://doi.org/10.1016/j.indcrop.2021.113329 (no. February).
[89] E. Neylon, E.K. Arendt, E. Zannini, A.W. Sahin, Fundamental study of the application of brewers spent grain and fermented brewers spent grain on the quality of pasta, Food Struct. 30 (2021) 100225, https://doi.org/10.1016/j.foostr.2021.100225.
[90] H.I. Chu and T. Miri, "Valorization of Bioactive Compounds Extracted from Brewer ' s Spent Grain (BSG) for Sustainable Food Waste Recycling," 2025.
[91] R.L. González-Díaz, et al., Valorization of brewer's spent grains through Ganoderma lucidum cultivation: Functional food ingredients and bread prototypes, LWT 214 (2024) 117131, https://doi.org/10.1016/j.lwt.2024.117131.
[92] D.L. Lamas, L.B. Gende, Valorisation of brewers' spent grain for the development of novel beverage and food products, Appl. Food Res. 3 (2) (2023) 100314, https://doi.org/10.1016/j.afres.2023.100314.
[93] J.S. Jaramillo-De la Garza, D.G. Rodríguez-Sánchez, C. Hernández-Brenes, E. Heredia-Olea, Development and Consumer Acceptability of Functional Bread Formulations Enriched with Extruded Avocado Seed Flour: Nutritional and Technological Properties, Foods (Basel Switz.) 14 (24) (Dec. 2025), https://doi.org/10.3390/foods14244282.
[94] Y. Yuan, et al., Innovative Food Processing Technologies Promoting Efficient Utilization of Nutrients in Staple Food Crops, Engineering 50 (2025) 229–244, https://doi.org/10.1016/j.eng.2025.04.014.
[95] B. Devnani, G.C. Moran, L. Grossmann, Extraction, Composition, Functionality, and Utilization of Brewer's Spent Grain Protein in Food Formulations, Foods (Basel Switz.) 12 (7) (Apr. 2023), https://doi.org/10.3390/foods12071543.
[96] J. Naibaho, M. Korzeniowska, A.B. Sitanggang, Y. Lu, E. Julianti, Brewers' spent grain as a food ingredient: Techno-processing properties, nutrition, acceptability, and market, Trends Food Sci. Technol. 152 (2024) 104685, https://doi.org/10.1016/j.tifs.2024.104685.
[97] J. Naibaho, M. Korzeniowska, Y. Phimolsiripol, M. Gavahian, Value-added compounds from brewers' spent grain to develop bioactive-enriched food ingredients: Recent advances in sustainable extraction and considerations for industrial application, Food Biosci. 71 (2025) 107351, https://doi.org/10.1016/j.fbio.2025.107351.
[98] M. Sajib, et al., Valorization of Brewer's spent grain to prebiotic oligosaccharide: Production, xylanase catalyzed hydrolysis, in-vitro evaluation with probiotic strains and in a batch human fecal fermentation model, J. Biotechnol. 268 (2018) 61–70, https://doi.org/10.1016/j.jbiotec.2018.01.005.
[99] M. Barrera-león, et al., "Transform. Brew. ' S. Spent Grain Solid. -State Ferment. Implic. Nutr. Health" (2025) 1–25.
[100] Y.L. Chin, K.F. Chai, W.N. Chen, Upcycling of brewers' spent grains via solid-state fermentation for the production of protein hydrolysates with antioxidant and techno-functional properties, Food Chem. X 13 (2022) 100184, https://doi.org/10.1016/j.fochx.2021.100184.
[101] N. Bazsefidpar, H.A. Gavlighi, A. Pouya, G. Yazdi, S. Mahdi, Optimization of protein extraction from brewer ' s spent grain and production of bioactive peptides," *Biomass Convers*, Biorefinery (2023), https://doi.org/10.1007/s13399-023-03932-4.
[102] M. Cermeño, et al., Identification of bioactive peptides from brewers' spent grain and contribution of Leu/Ile to bioactive potency, J. Funct. Foods 60 (2019) 103455, https://doi.org/10.1016/j.jff.2019.103455.
[103] R.A. Carciochi, C.A. Sologubik, M.B. Fernández, G.D. Manrique, L. G. D'Alessandro, Extraction of Antioxidant Phenolic Compounds from Brewer's Spent Grain: Optimization and Kinetics Modeling, Antioxid. (Basel Switz.) 7 (4) (Mar. 2018), https://doi.org/10.3390/antiox7040045.
[104] A. Zuorro, A. Iannone, and R. Lavecchia, "Water – Organic Solvent Extraction of Phenolic Antioxidants from Brewers ' Spent Grain," 2019, doi:10.3390/pr7030126.
[105] M.J. Rahman, L.N. Malunga, M. Eskin, P. Eck, S.J. Thandapilly, U. Thiyam-Hollander, Valorization of Heat-Treated Brewers' Spent Grain Through the Identification of Bioactive Phenolics by UPLC-PDA and Evaluation of Their Antioxidant Activities, Front. Nutr. 8 (2021) 634519, https://doi.org/10.3389/fnut.2021.634519.
[106] C.F. Paiva, et al., Potential of Brewer's Spent Grain as a Nutritional Ingredient in Bakery Products, Plant. Foods Hum. Nutr. 80 (1) (Dec. 2024) 12, https://doi.org/10.1007/s11130-024-01251-1.
[107] A.M.M. da Silva, M.A. Lima, F. Koksel, A.C.K. Sato, Incorporation of brewer's spent grain into plant-based meat analogues: benefits to physical and nutritional quality, Int. J. Food Sci. Technol. 59 (6) (Jun. 2024) 3870–3882, https://doi.org/10.1111/ijfs.17134.
[108] M.-L. Păcală, A. Sîrbu, A. Şipoş, Non-Conventional Brewers' Spent Grains, an Alternative Raw Material in Bread-Making, Foods (Basel Switz.) 13 (21) (Oct. 2024), https://doi.org/10.3390/foods13213442.
[109] S. Chattaraj, D. Mitra, M. Chattaraj, A. Ganguly, H. Thatoi, P.K. Das Mohapatra, Brewers' spent grain as fish feed ingredient: Evaluation of bio-safety and analysis of its impact on gut bacteria of Cirrhinus reba by 16S Metagenomic sequencing, Curr. Res. Microb. Sci. 7 (2024) 100286, https://doi.org/10.1016/j.crmicr.2024.100286.
[110] Y. Shen, et al., Feed nutritional value of brewers' spent grain residue resulting from protease aided protein removal, J. Anim. Sci. Biotechnol. 10 (1) (2019) 78, https://doi.org/10.1186/s40104-019-0382-1.
[111] A. Estévez, L. Padrell, B. Iñarra, M. Orive, D.S. Martin, Brewery by-products (yeast and spent grain) as protein sources in gilthead seabream (Sparus aurata) feeds, Aquaculture 543 (2021) 736921, https://doi.org/10.1016/j.aquaculture.2021.736921.
[112] E.D. Osei, A.S. Naik, G. Kinsella, T. Delaney, S. Kirwan, Potential of Brewer's spent grain bioactive fractions as functional ingredients for companion and farm animal foods – A review, Appl. Food Res. 5 (2) (2025) 101138, https://doi.org/10.1016/j.afres.2025.101138.
[113] J.-B. Xiong, L. Nie, J. Chen, "Current understanding on the roles of gut microbiota in fish disease and immunity, Zool. Res. 40 (2) (Mar. 2019) 70–76, https://doi.org/10.24272/j.issn.2095-8137.2018.069.
[114] S. Mitri, et al., Valoriz. Brew. ' Spent Grains Pretreat. Ferment. a Rev. (2022).
[115] S. Ikram, L. Huang, H. Zhang, J. Wang, M. Yin, Composition and Nutrient Value Proposition of Brewers Spent Grain, J. Food Sci. 82 (10) (Oct. 2017) 2232–2242, https://doi.org/10.1111/1750-3841.13794.

[116] J.K. Katu, T. Tóth, B. Ásványi, Z. Hatvan, L. Varga, Effect of Fermented Feed on Growth Performance and Gut Health of Broilers: A Review, Anim. Open. Access. J. MDPI 15 (13) (Jul. 2025), https://doi.org/10.3390/ani15131957.

[117] Y. Li, M. Dong, Y. Wang, Q. Liu, Effects of fermented brewer's spent grains on growth performance, intestinal development and liver metabolism in broilers, J. Agric. Food Res. 23 (2025) 102156, https://doi.org/10.1016/j.jafr.2025.102156.

[118] M.R. Bedford, B. Svihus, A.J. Cowieson, Dietary fibre effects and the interplay with exogenous carbohydrases in poultry nutrition, Anim. Nutr. 16 (2024) 231–240, https://doi.org/10.1016/j.aninu.2023.09.007.

[119] R. Jha, P. Mishra, Dietary fiber in poultry nutrition and their effects on nutrient utilization, performance, gut health, and on the environment: a review, J. Anim. Sci. Biotechnol. 12 (1) (2021) 51, https://doi.org/10.1186/s40104-021-00576-0.

[120] A.U. Sadiq, Circular Economy Adoption in Agriculture: Potential for Sustainable Food Production in Nigeria, W. N. M 7 (1) (2025).

[121] F. Karlsen, P.V. Skov, Review – Potentials and limitations of utilising brewer's spent grain as a protein source in aquaculture feeds, J. Clean. Prod. 357 (2022) 131986, https://doi.org/10.1016/j.jclepro.2022.131986.

[122] F.P. Martínez-Antequera, et al., Effect of Two Different Pretreatments of Brewers Spent Grain Used as Feed Ingredient on Nutritional, Immunological, and Metabolical Parameters in Gilthead Seabream (Sparus aurata), Biol. (Basel) 14 (6) (May 2025), https://doi.org/10.3390/biology14060585.

[123] H. Fernandes, et al., Solid - state fermented brewer ' s spent grain enzymatic extract increases in vitro and in vivo feed digestibility in European seabass, Sci. Rep. (2021) 1–16, https://doi.org/10.1038/s41598-021-02393-x.

[124] G. Kitaw, M. Faji, G. Terefe, Nutritional and fungal load dynamics of fresh brewers' grain stored under aerobic conditions, AMB Express 12 (1) (Feb. 2022) 10, https://doi.org/10.1186/s13568-022-01356-3.

[125] R. Shekhar, V.B. Raghavendra, P. Rachitha, A comprehensive review of mycotoxins, their toxicity, and innovative detoxification methods (no. January, p), Toxicol. Rep. 14 (2025) 101952, https://doi.org/10.1016/j.toxrep.2025.101952.

[126] A.A. Goda, et al., Global health and economic impacts of mycotoxins: a comprehensive review, Environ. Sci. Eur. 37 (1) (2025) 122, https://doi.org/10.1186/s12302-025-01166-x.

[127] J. Naibaho, Brew. ' spent grain Food Syst. Process. Final. Prod. Qual. a Funct. Fiber Modif. Treat." no. Oct. 2020 (2021) 1532–1551, https://doi.org/10.1111/1750-3841.15714.

[128] G. Terefe, Preservation techniques and their effect on nutritional values and microbial population of brewer's spent grain: a review, CABI Agric. Biosci. 3 (1) (2022) 51, https://doi.org/10.1186/s43170-022-00120-8.

[129] P. Dancker, K. Glas, M. Gastl, Potential utilisation methods for brewer's spent grain: a review, Int. J. Food Sci. Technol. 60 (1) (Jan. 2025) vvae022, https://doi.org/10.1093/ijfood/vvae022.

[130] A. Chetrariu, A. Dabija, Spent Grain: A Functional Ingredient for Food Applications, Foods (Basel Switz.) 12 (7) (Apr. 2023), https://doi.org/10.3390/foods12071533.

[131] D. Outeiriño, I. Costa-Trigo, R. Oliveira, N. Pérez Guerra, J. Domínguez, A novel approach to the biorefinery of brewery spent grain, Process. Biochem. (Jun. 2019), https://doi.org/10.1016/j.procbio.2019.06.007.

[132] S. Saldarriaga-hernandez, et al., Integr. Biorefinery Brew. ' S. Spent Grain Second. -Gener. Ethanol Mycoprotein Bioact. Vinasse Prod. (2025) 1–24.

[133] W. Hammann, A. Ross, W. Seames, Sequential Extraction of Carbohydrates and Lipids from Chlorella vulgaris Using Combined Physical and Chemical Pre-Treatments, ChemEngineering 8 (1) (2024), https://doi.org/10.3390/chemengineering8010011.

[134] A. Vasileiadou, "From Organic Wastes to Bioenergy, Biofuels, and Value-Added Products for Urban Sustainability and Circular Economy: A Review," 2024.

[135] D. Outeiriño, et al., Biorefinery of brewery spent grain to obtain bioproducts with high value-added in the market, N. Biotechnol. 79 (2024) 111–119, https://doi.org/10.1016/j.nbt.2023.12.010.

[136] S. Bachmann, T. Calvete, L. Féris, Potential applications of brewery spent grain: Critical an overview (Dec), J. Environ. Chem. Eng. 10 (2021) 106951, https://doi.org/10.1016/j.jece.2021.106951.

[137] J. Weiermüller, A. Akermann, W. Laudensack, J. Chodorski, L.M. Blank, R. Ulber, Brewers' spent grain as carbon source for itaconate production with engineered Ustilago maydis, Bioresour. Technol. 336 (2021) 125262, https://doi.org/10.1016/j.biortech.2021.125262.

[138] M.O. Bamidele, et al., Bioengineering in Solid-State Fermentation for next sustainable food bioprocessing, no. October 2024, p, Sustain 6 (2025) 100105, https://doi.org/10.1016/j.nxsust.2025.100105.

[139] D.C. Makepa, C.H. Chihobo, Barriers to commercial deployment of biorefineries: A multi-faceted review of obstacles across the innovation chain, Heliyon 10 (12) (2024) e32649, https://doi.org/10.1016/j.heliyon.2024.e32649.

[140] P. Parthasarathy, S. Zuhara, T. Al-Ansari, G. McKay, A review on catalytic CO2 pyrolysis of organic wastes to high-value products, Fuel 335 (2023) 127073, https://doi.org/10.1016/j.fuel.2022.127073.

[141] S. Yu, Q. Li, Y. Zhang, J. Yan, H. Zhou, Enhancing carbon-negative emission technologies through biomass integration, Innov 6 (12) (2025) 101079, https://doi.org/10.1016/j.xinn.2025.101079.

[142] B. Iñarra, et al., Ecodesign of new circular economy scheme for Brewer's side streams, Sustain. Chem. Pharm. 28 (2022) 100727, https://doi.org/10.1016/j.scp.2022.100727.

[143] D. Agrawal, D. Gopaliya, N. Willoughby, S.K. Khare, V. Kumar, Recycling potential of brewer's spent grains for circular biorefineries, Curr. Opin. Green. Sustain. Chem. 40 (2023) 100748, https://doi.org/10.1016/j.cogsc.2022.100748.

[144] A. Lima Moraes dos Santos, A. de Sousa e Silva, N.W. Sales Morais, A. Bezerra dos Santos, Brewery Spent Grain as sustainable source for value-added bioproducts: Opportunities and new insights in the integrated lignocellulosic biorefinery concept, Ind. Crops Prod. 206 (2023) 117685, https://doi.org/10.1016/j.indcrop.2023.117685.

[145] J. Evaristo, et al., Water woes: the institutional challenges in achieving SDG 6, Sustain. Earth Rev. 6 (1) (2023), https://doi.org/10.1186/s42055-023-00067-2.

[146] N.P.P. Pabbathi, et al., Brewer's spent grains-based biorefineries: A critical review, Fuel 317 (2022) 123435, https://doi.org/10.1016/j.fuel.2022.123435.

[147] J. Buffington, The Economic Potential of Brewer ' s Spent Grain (BSG) as a Biomass Feedstock, no. July (2014) 308–318.

[148] M. Taifouris, M.L. Corazza, M. Martín, Integrated Design of Biorefineries Based on Spent Coffee Grounds, Ind. Eng. Chem. Res. 60 (1) (Jan. 2021) 494–506, https://doi.org/10.1021/acs.iecr.0c05246.

[149] R. Benjamin, W. Evaristo, P. Gustavo, B. Dantas, G.F. Ghesti, Biorefinery Development Based Brewers ' Spent Grain (BSG) Conversion A Forecasting Technology Study Brazilian Scenario (2025) 217–237.

[150] M. Jackowski, et al., Synergetic Co-Production of Beer Colouring Agent and Solid Fuel from Brewers' Spent Grain in the Circular Economy Perspective, Sustainability 13 (18) (2021) 10480, https://doi.org/10.3390/su131810480.

[151] A. Leite, A. Modzelewska, M. Jackowski, Upcycling of brewing byproducts into the brewing process: A sustainable beer brewing approach, Food Bioprod. Process. 159 (2026) 81–94, https://doi.org/10.1016/j.fbp.2026.06.009.

[152] M. Mainardis, M. Hickey, R.K. Dereli, Lifting craft breweries sustainability through spent grain valorisation and renewable energy integration: A critical review in the circular economy framework, no. August 2023, J. Clean. Prod. 447 (2024), https://doi.org/10.1016/j.jclepro.2024.141527.

[153] L.P. Lins, D.G. Martinez, A.C. Furtado, J.C. Padilha, Biomethane generation and CO2 recovery through biogas production using brewers' spent Grains, Biocatal. Agric. Biotechnol. 48 (2023) 102579, https://doi.org/10.1016/j.bcab.2022.102579.

[154] A. Barbosa, E. Monteiro, A Sustainable Power Production System Based on Integrated Supercritical Water Gasification of Brewer's Spent Grains and Carbon Dioxide Capture, Energy Technol. 14 (1) (2025), https://doi.org/10.1002/ente.202501039.

[155] F. Barontini, S. Vitolo, M. Puccini, Valorisation of the under-sieve fraction of mixed municipal solid waste by hydrothermal carbonization, J. Ind. Eng. Chem. 152 (2025) 245–255, https://doi.org/10.1016/j.jiec.2025.04.055.

[156] A. Lorente, et al., "Sustainable Production of Solid Biofuels and Biomaterials by Microwave-Assisted, Hydrothermal Carbonization (MA-HTC) of Brewers' Spent Grain (BSG),", ACS Sustain. Chem. &amp Eng. 8 (51) (2020) 18982–18991, https://doi.org/10.1021/acssuschemeng.0c06853.

[157] J.Y. Kim, M. Kim, J. Lee, J.H. Park, E.E. Kwon, Reducing CO2 emissions in brewing industry through sustainable valorisation of brewer's spent grain using CO2-assisted pyrolysis, J. Anal. Appl. Pyrolysis 190 (2025) 107165, https://doi.org/10.1016/j.jaap.2025.107165.

[158] G. Cabrera, J.M. Jáimez, J. Sánchez-Oneto, J. Bolivar, A. Valle, Revalorisation of brewer's spent grain for biotechnological production of hydrogen with Escherichia coli, Front. Bioeng. Biotechnol. 12 (2024) 1473704, https://doi.org/10.3389/fbioe.2024.1473704.

[159] P. Alonso-Riaño, R. Melgosa, E. Trigueros, A.E. Illera, S. Beltrán, M.T. Sanz, Valorization of brewer's spent grain by consecutive supercritical carbon dioxide extraction and enzymatic hydrolysis, Food Chem. 396 (Dec. 2022) 133493, https://doi.org/10.1016/j.foodchem.2022.133493.

[160] D. Hidalgo, A. Urueña, J.M. Martín-Marroquín, D. Díez, Integrated Approach for Biomass Conversion Using Thermochemical Routes with Anaerobic Digestion and Syngas Fermentation, Sustainability 17 (8) (Apr. 2025) 3615, https://doi.org/10.3390/su17083615.

[161] A. Akbari, H. Sarvi, M. Maleki, S. Bahreyni, R. Azimi, A. Radpour, Characteristics, emissions, capture, storage, and utilization of carbon dioxide: A comprehensive review of challenges and technologies for greenhouse gas mitigation, Pet. Res. 11 (1) (2026) 116–138, https://doi.org/10.1016/j.ptlrs.2025.07.001.

[162] E. Newman, N. Nitin, E. Spang, G. Fox, Carbon Footprint Assessment on the Viability of Utilizing Brewer's Spent Grain to Produce Biochar, Appl. Sci. 15 (10) (2025), https://doi.org/10.3390/app15105525.

[163] E. Wagner, M. EugeniaPería, G. Ortiz, L. Rojas, P. Ghiringhelli, B. Elwakil, "Valorization of brewer's spent grain by different strategies of structural destabilization and enzymatic saccharification,", Ind. Crops Prod. 163 (May 2021) https://doi.org/10.1016/j.indcrop.2021.113329.

[164] M. Plata, Ł. Korzeniowski, K. Sangam, M. Lewandowski, P. Maziarka, M. Wądrzyk, From beer to biocrude through hydrothermal liquefaction of brewers' spent grain enhanced with acid hydrolysis pretreatment, Fuel 391 (2025) 134710, https://doi.org/10.1016/j.fuel.2025.134710.

[165] B.R. Tiwari, et al., Life Cycle Assessment of Microbial 2,3-Butanediol Production from Brewer's Spent Grain Modeled on Pinch Technology, ACS Sustain. Chem. Eng. 11 (22) (Jun. 2023) 8271–8280, https://doi.org/10.1021/acssuschemeng.3c00616.

[166] Y.A. da Fonseca, A.R.A.C. Fernandes, L.V.A. Gurgel, B.E.L. Baêta, Comparative life cycle assessment of early-stage technological layouts for brewers' spent grain upcycling: a sustainable approach for adding value to waste, J. Water Process. Eng. 66 (2024) 105904, https://doi.org/10.1016/j.jwpe.2024.105904.

[167] D. Kaffe, 2025, Comparative Life Cycle Assessment of Agro-Industrial Residues: Environmental Impacts of Grape Marc and Brewer ' s Spent Grain Combustion," pp. 1–39.

[168] D.B. Maru, et al., Occurrence of Mycotoxins in Sunflower Seed Cake: A Study from Bahir Dar and Its Vicinities, Northwest Ethiopia, Appl. Food Res. 5 (2) (2025) 101207, https://doi.org/10.1016/j.afres.2025.101207.
[169] F. Peles, et al., Adverse effects, transformation and channeling of aflatoxins into food raw materials in livestock (no. December), Front. Microbiol. 10 (2019) 1–26, https://doi.org/10.3389/fmicb.2019.02861.
[170] N. Haring, B. Drábová, M. Chňapek, Circular VAlorization of Brewer's Spent Grain and Brewer's Yeast: pathways, sustainability implications, techno-economic feasibility, and policy perspectives, Sustain 18 (5) (2026) 1–19, https://doi.org/10.3390/su18052464.