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Repurposing the by-products of alcoholic beverage industries: A circular economy framework to reach sustainable development goals

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ABSTRACT

The alcoholic beverage industry has a significant role in the global economy and culture. As a part of beverage production, substantial solid and liquid by-products are also generated in parallel streams to the beverage. The by-products, viz. spent grains, pomace, and yeast slurry, have conventionally been treated as waste streams, leading to environmental concerns and resource inefficiency. The paper reviews a choice of pathways for the sustainable management of by-products generated by brewery, distillery, and winery. It offers an integrated circular economy framework to repurpose these by-products to achieve the Sustainable Development Goals (SDG). The alignment of sustainable practices in the alcoholic beverage industry directly correlates with the SDGs, particularly those related to the zero hunger (SDG 2), affordable and clean energy (SDG 7) and responsible consumption and production (SDG 12). Potential benefits of repurposing alcoholic beverage by-products into high-value food products, animal feed, antioxidants, polyphenols, and renewable energy sources have also been assessed. Prospectives of the alcoholic beverage industry by-products as valuable resources that can contribute to a more sustainable and circular approach to production and consumption have been underlined. Incorporation of these practices would not only help to minimize the environmental footprint of beverage industry but also make significant strides towards achieving key sustainable development goals, ultimately benefiting society and the planet.

1. Introduction

As the global population grows; the challenge of sustaining food production becomes increasingly complex. The United Nations projects that the world population will reach 9.7 billion by 2050, putting immense pressure on agricultural systems to meet the escalating demand for food (Jones et al., 2022). The global food production challenge arises from a combination of factors, including population growth, changing dietary preferences, climate change, and limited natural resources. Food production must double by 2050 to meet the projected demand, but traditional agricultural practices alone may not be sufficient to achieve this goal (Zan et al., 2022). The expansion of arable land is limited, and excessive land use can lead to deforestation and ecological degradation. Additionally, intensive farming practices can deplete soil fertility and contribute to greenhouse gas emissions, exacerbating climate change.

To address this challenge, innovative and sustainable solutions are required. One such solution is utilizing by-products from distilleries, breweries, and wineries to mitigate the strain on food production systems. Alcoholic beverage industries, viz., distillery, brewery, and winery, generate huge amounts of solid and liquid by-products (Kang et al., 2022). These by-products are generally high in chemical and biochemical oxygen demand, ammonia, phosphorus, lignin, yeast, and protein (Kang et al., 2022). The characteristics of the waste stream from the

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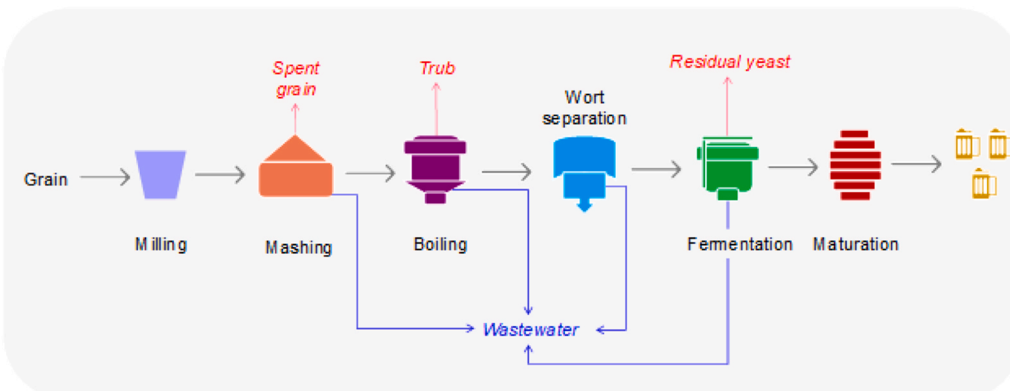
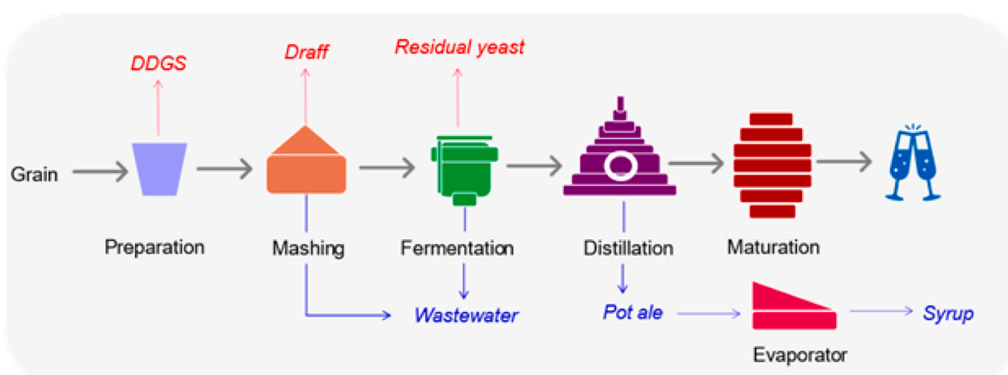
alcoholic beverage industry make it one of the highly polluting industries. Distillery, brewery, and winery can significantly mitigate global food and energy crises through the sustainable use of their by-products in a circular economy framework (Kavalopoulos et al., 2021).

Distilleries and breweries produce large quantities of by-products, i.e., spent grains, stillage, yeast, trub, and vinasse, during the alcohol production process (Fig. 1(a) and (b)) (Rodriguez et al., 2023). Historically, these by-products have been treated as waste, posing environmental challenges due to their high organic content. However, recent research and innovative technologies have demonstrated that these by-products can be effectively utilized in various ways to enhance food production sustainably (Duffy et al., 2023). Spent grains and stillage contain valuable nutrients that can serve as nutritious feed for livestock, including cattle, pigs, and poultry.

These by-products are also rich in protein, fibre, and minerals, which can supplement traditional animal feeds and reduce the pressure on conventional feed sources (Benavides et al., 2020). Brewery by-products can also be utilized in aquaculture. Yeast, for example, contains essential amino acids and vitamins, making it a suitable ingredient in fish feed, thus promoting sustainable aquaculture practices (San Martin et al., 2020). Vinasse and trub are by-products of the brewing and distillation process, respectively, and are rich in organic matter and potassium. Following composting, these can be utilized as a soil amendment, promoting soil health and reducing the dependence on chemical fertilizers (Carpanez et al., 2022). Wineries generate significant quantities of by-products, including grape pomace, stems, and seeds (Fig. 1(c)) (Baptista et al., 2023). These by-products offer various potential



(a)



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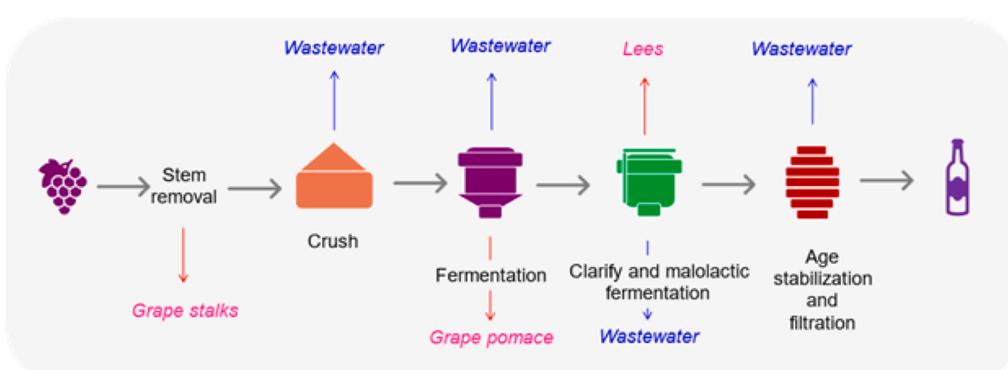

(c)

Fig. 1. Process flow of the by-products generation from (a) brewery; (b) distillery; and (c) winery.

applications to mitigate the global food production challenge. After the juice extraction during winemaking, the remaining grape pomace still contains valuable nutrients that can be utilized as a feed supplement for livestock, helping to diversify animal diets and reduce the environmental impact of feed production. Grape seeds and skins contain polyphenols and antioxidants, which have numerous health benefits. These by-products can be used as natural additives in food and beverages, providing a sustainable alternative to synthetic antioxidants (Yang et al., 2021).

This paper reviews the various ways to sustainably manage brewery, distillery, and winery industries. The study offers an integrated comparative circular economy framework, which can result in upcycling the alcoholic beverage industry by-products in order to achieve the SDGs, focusing on food, animal feed, and energy vector recovery. Further, the review also gives insight into technological upgrades and policy changes in the field.

2. Bibliometric study

2.1. Methodology

Bibliometric investigation is an essential research method used to evaluate and quantify the impact and influence of scholarly publications within a specific field of study. The analysis was performed using a scientific dataset of primary academic and scholarly research publications retrieved from Clarivate Analytics' ISI – Web of Science. Web of Science, often referred to as WoS, is a well-known and widely used bibliographic database for academic and scholarly research. It covers a vast array of academic disciplines and includes journals, conference proceedings, reports, and books. It accomplishes both goals by giving users access to a wide selection of academic literature. "Advanced search" was followed along with following logical operation: ALL= ("Alcoholic beverage industry"); ((ALL=("Distillery")) OR ALL= ("Winery")) OR ALL= ("Brewery"); ALL= ("Brewer's spent grains"); (ALL= ("Alcohol industry")) AND ALL= ("byproducts"); (ALL=("Winery waste")) AND ALL= ("biofuel"); (ALL=("Winery waste")) AND ALL= ("antioxidants"); (ALL=("Distillery waste")) AND ALL= ("energy recovery"); (ALL=("Brewery waste")) AND ALL= ("circular economy"); (ALL= ("Brewery waste")) AND ALL= ("animal feed"); (ALL=("Winery waste")) AND ALL= ("polyphenols"); (ALL=("Brewery waste")) AND ALL= ("byproducts"); (ALL=("Distillery waste")) AND ALL= ("value added products"); and so on. Specific phrases (title, abstract, keywords) were analyzed for desirable outcomes using the aforementioned queries "Article" and "Review" was only considered documents. The search was conducted from 2003 to 2023 in order to find common phrases related to particular fields of research and analyze changes in publication frequency. Within the selected time frame, 507 works in total (454 articles and 48 reviews) were published. The authors used data gathered and analysed from collected documents in VOSviewer software to generate their keyword clusters. The bibliometric study was solely based on data from Web of Science (WoS).

2.2. Co-occurrence keywords analysis

The concurrence of different keywords was analyzed to mark popular research topics and retrieval for identifying trends, patterns, and knowledge gaps within a specific field of study (Table 1a,b). These gaps suggest areas where research may be limited, and further investigation is needed to advance understanding. Keywords that co-occur frequently may indicate areas of research that are closely related or interconnected in scholarly publications. Co-occurrence keyword analysis is often accompanied by data visualization techniques, viz. co-occurrence networks and cluster analysis. These visualizations make it easier to interpret and communicate the findings, allowing researchers to see the structure of the research landscape. During the last 20 years, this search has yielded 1572 keywords. The top 20 most often used terms are shown in Table 1a,b. Fig. 2a depicted the clustering of the 62 most commonly used terms into 7 groups. Each cluster was connected to a particular field of study and a term had to appear at least five times in order to be included in the analysis. This analysis got keyword "anaerobic digestion" with highest frequency and link strength, suggested that it is a highly prominent keyword within the corpus of scholarly publications being involved. It's important to remember that while "anaerobic digestion" may be a central keyword because it links distillery, brewery and winery with the core process of fermentation to produce by-products and so additional analysis is needed to understand the specific aspects of research, trends, and applications associated with it. Other keywords, i.e., biorefinery, biogas, biomass and brewer's spent grains, were also frequently used keywords with good link strength, and its interconnection indicated the use of brewery by-products, viz., spent grains and yeast slurry, in biorefinery for the generation of biogas and hydrocar as a sustainable solution. However, the keyword "Circular economy" of cluster (7), with frequency (16) illustrated association with keywords i.e. antimicrobial activity, antioxidant activity, brewer's spent grain, phenolic compounds, protein, which represented application of by-products obtained from alcoholic beverage industry waste (namely

Table 1a
The top 20 keywords, together with their overall frequency (occurrence) and link strength.

Number	Keywords	Occurences	Total Link Strength
1	Anaerobic digestion	31	45
2	Biorefinery	25	42
3	Biogas	14	40
4	Biomass	20	34
5	Brewer's spent grains	37	33
6	Circular economy	16	30
7	Hydrothermal carbonization	15	29
8	Winery waste	19	27
9	Bioenergy	10	22
10	Methane	6	20
11	Waste valorization	8	19
12	Grape pomace	12	17
13	Hydrochar	9	16
14	Polyphenols	17	16
15	Biofuel	7	14
16	Antioxidant activity	12	12
17	Biohydrogen	5	12
18	Vinasse	9	8
19	Winery waste	18	8
20	Distillery spent wash	5	4

Table 1b
Clusters of the most important keywords produced with VOSviewer software.

Clusters	No. of items	Keywords on the VOSviewer Network
1	11	Biogas, Biohydrogen, Biomethane, Distillery effluent, Energy, Enzymes, Methane, Sugarcane, Vinasse, Wastewater treatment, Winery wastewater.
2	11	Biochar, Bioethanol, Hydrochar, Hydrolysis, Hydrothermal carbonization, Lignocellulosic biomass, Lignocellulose, Pyrolysis, Spent grain, Water valorization.
3	10	Anaerobic digestion, Brewer's spent grains, Distillery spent wash, Enzymatic hydrolysis, Ethanol, Fermentation, Immobilization, *Saccharomyces cerevisiae*, Valorization, Yeast.
4	9	Brewery waste, Brewery wastewater, Distillery wastewater, Chemical oxygen demand, Lactic acid bacteria, Sustainability, Valorization, Wastewater, Winery.
5	8	Bioconversion, Bioenergy, Biofuel, Biorefinery, Biofuels, Food waste, Pretreatment, Value added products.
6	7	Antioxidants, Compost, Grape pomace, Lignin, Polyphenols, Winery effluent, Winery waste.
7	6	Antimicrobial activity, Antioxidant activity, Brewer's spent grain, Circular economy, Phenolic compounds, Protein.

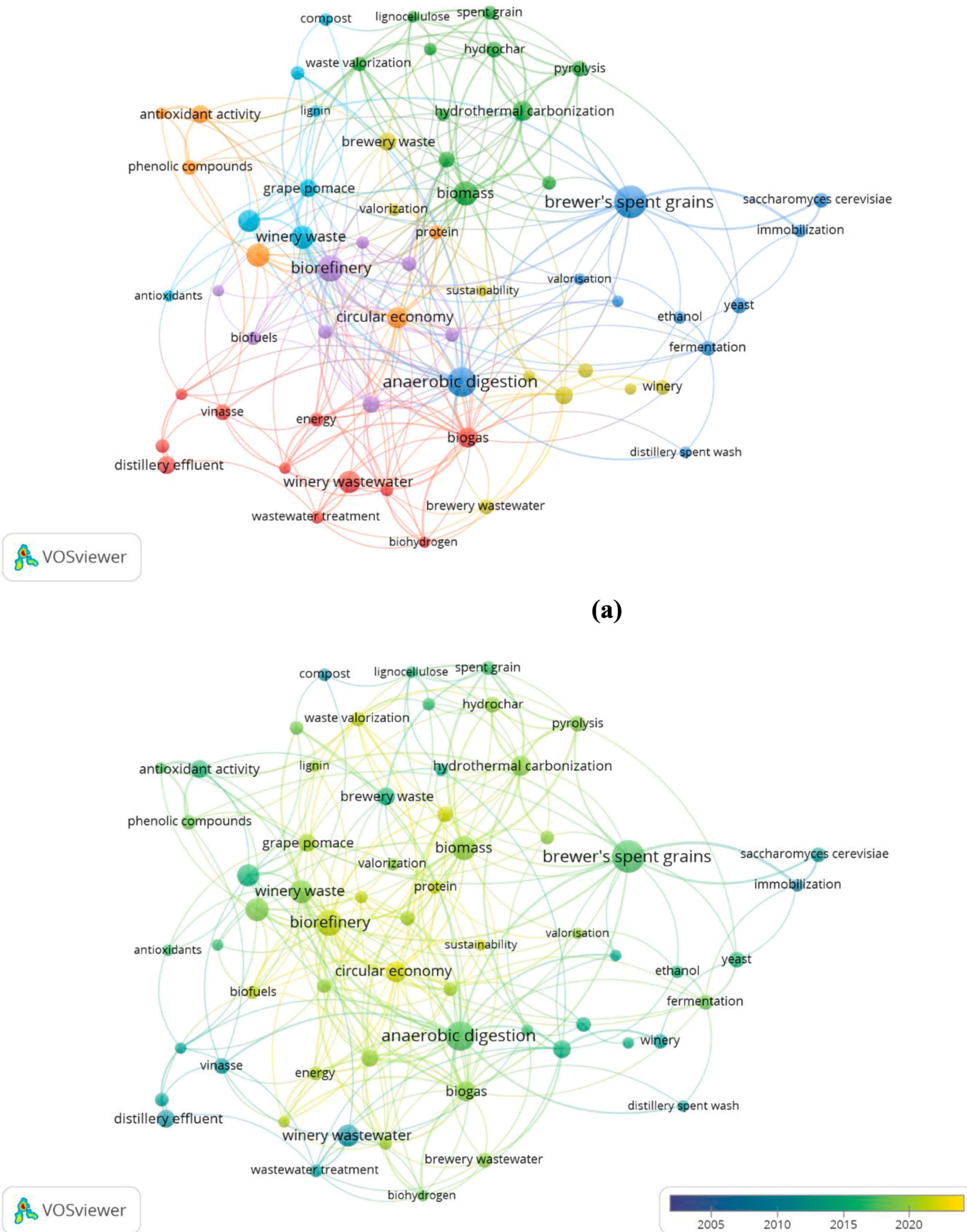

Fig. 2. Clustering of the 62 most frequent author's keywords. (a) term map based on different clusters; (b) term map based average publication year.

brewery, distillery and winery) that generate economy by converting waste into best output.

Fig. 2b has illustrated the superimposed visualization map employing important keywords. Mean number of publications from 2015 to 2020 were further presented through range of colors from sky blue to greenish yellow. Progress towards the processing of waste materials from the alcohol beverage industry through a biorefinery approach could offer economic as well as environment objectives. This approach aligns with the principles of the circular economy and promotes sustainability through utilization of by-products and the conversion of waste into important resources, viz. animal feed, phenolic compounds, antioxidants and energy recovery.

3. Food and animal feed recovery from distillery, brewery, and winery by-products

3.1. Protein recovery

Proteins are nitrogen-containing substances, crucial for the production of an array of enzymes and hormones and essential for animal and human growth. Proteins should be metabolized into their simplest form, i.e., amino acids, for human growth and metabolism (Calvez et al., 2024). Insufficient amino acid availability could lead to malnourishment and poor functioning of the human body. In extreme hunger, the body will consume itself to obtain the protein required for enzymes and necessary hormone functions. Therefore, protein deficiency, i.e., relative or absolute deficiency in the body's protein or one or more essential amino acids, may arise either due to dietary protein deficiency or diseases and is indicative of a global protein-enriched food deficit. Protein deficiency can also occur due to poor protein quality despite adequate protein intake (Calvez et al., 2024). On the one hand, due to the modern unhealthy or unbalanced food practices and the unavailability of sufficient protein-enriched food, there is an upsurge in demand for protein supplements. On the other hand, treating industrial waste, i.e., distilleries, breweries, and wineries, is a prime global concern and has been explored extensively (Table 2a). Therefore, exploring these industries' by-products for protein recovery could help fulfil the protein requirements and address environmental issues.

3.1.1. Protein recovery from distillery by-products

The distillery industry wastes, i.e., raff, pot ale, stillage or spent wash, spent lees, yeast sludge, Distiller's dried grains with soluble (DDGS), and corn oil; contain large quantities of nitrogen, phosphorus, and organics. The distillery industry's wastes mainly consist of essential amino acids, viz. lysine, methionine, cysteine, histidine, and threonine (White et al., 2016). Pot ale, a co-product of malt whiskey, can be found as a syrup and an insoluble solid fraction. The syrup is mainly evaporated and used as feed or land/sea disposal, or treated by anaerobic digestion (AD). The major portion of the insoluble solid fraction is yeast, which contains 55 % protein and thus can be used as a protein feed

Table 2a
Protein recovery from distillery, brewery and winery by-products.

By-product	Extraction method	Protein	Protein yield/ concentration	Reference
Distillers dried grains with solubles (DDGS)	Ultrasonic-assisted enzymatic extraction (amplitude- 90.01 %, solid loading- 10 % and time−18.06 min) Enzyme-proteases	DDGS protein hydrolysates	65.76 %, w/w	(Singh et al., 2022)
DDGS Wet solids (WS)	Aqueous-ethanol extraction (70 %, v/v at 70 °C and 1 % sodium metabisulphite)	DDGS protein WS protein	47.7 %, w/w 59.8 %, w/w	(Singh et al., 2019)
Brewers' spent grains (BSG)	Hydro-mechanical processing (vertical toothed colloid mill, 3000 rpm, fitted with a 7 l hopper)	BSG total protein Amino acid: Arginine Aspartine Glutamine Leucine Proline	38 % 5.9 % 8.8 % 19.4 % 8.0 % 9.2 %	(Ibbett et al., 2019)
Brewer's spent grain	Ultrafiltration (5 and 30 kDa membrane with a surface area of 0.05 m^2) (BSG: 73.8 % moisture, 7.6 % protein, wet weight basis)	BSG protein Protein recovery: 5 kDa membrane 30 kDa membrane	92 % retained by membrane 20.09 ± 1.40 % 15.98 ± 0.58 %	(Tang et al., 2009)
Grape seed meal	Alkaline extraction followed by isoelectric precipitation (pH 10, temp. of 36 °C, meal/water ratio of 1:9 and extraction time of 2 h)	Grape seed protein concentrate Amino acid: Aspartic acid Glutamic acid Phenylalanine Arginine	55.35 ± 0.10 % 7.18 ± 0.28 g 100 g^{-1} protein 27.93 ± 0.98 g 100 g^{-1} protein 3.89 ± 0.15 g 100 g^{-1} protein 7.29 ± 0.27 g 100 g^{-1} protein	(Baca-Bocanegra et al., 2021)
Chaenomeles japonica press residue	Supercritical CO_2 extraction (35 Pa, 50 °C, CO_2 flow rate of 200 g min^{-1} and temperature 40 °C)	Protein isolate Amino acid: Leucine Phenylalanine Tyrosine Arginine Aspartic acid Glutamic acid	6.04 ± 0.99 g 100 g^{-1} 7.32 ± 0.34 mg 100 mg^{-1} 4.74 ± 0.12 mg 100 mg^{-1} 3.33 ± 0.11 mg 100 mg^{-1} 10.02 ± 0.11 mg 100 mg^{-1} 9.77 ± 0.17 mg 100 mg^{-1} 28.98 ± 1.26 mg 100 mg^{-1}	(Ben-Othman et al., 2023)

ingredient. In contrast, the liquid fraction is also protein-enriched and mainly contains protein similar to beer. Pot ale syrup from Scottish malt whisky distilleries contains dry matter (42 %), protein (13.4 %), and copper (41 mg kg^{-1}). Liquid fraction also contains other value-added components, i.e., phosphorus, potassium, and polyphenols (White et al., 2020). Characterization of pot ale revealed that ~ 33.0 % of dry matter is crude protein (White et al., 2020). Moreover, the study also recorded significant amounts of amino acids, i.e., arginine, methionine, phenylalanine, isoleucine, leucine, and threonine. Similarly, another study reported the mean concentration (28 g L^{-1}) of soluble protein along with a significant amount of proline (688 mg L^{-1}) and lysine (200 mg L^{-1}) in the pot ale from scotch whisky distilleries (Edwards et al., 2022).

Another widely used distillery product is tequila, which produces vinasse as waste. Tequila vinasse can be employed for the simultaneous treatment and revalorization by using fodder yeasts, i.e., *Rhodotorula mucilaginosa, Candida utilis*, *Kluyveromyces marxianus*, etc., to convert it into protein-enriched animal feed (Díaz-v et al., 2022). The study observed the successful conversion of tequila vinasse to yeast-based protein (18.08 ± 2.73 g L^{-1}) enriched feed. The study also observed higher glutamic acid, valine, threonine, and tyrosine in the case of mixed culture treatment compared to the monoculture treatment (Díaz-v et al., 2022). Recently, the condensed corn distillers' solubles, also known as corn stillage, have been explored for their protein recovery potential (Sharma et al., 2023). The study analyzed the protein fraction composition followed by hydrolysis through trypsin to investigate the potential of bioactives. The corn stillage is composed of dry matter (33 %) and moisture (67 %). In the dry matter, the protein fraction contributes to 25.43 %, with a protein content of 54.63 ± 1.29 % of dry matters. The amino acid analysis revealed that glutamic acid (7.56 ± 0.08 %) and leucine (7.09 ± 0.02 %) were most abundant, along with significant amounts of proline, phenylalanine, alanine, aspartic acid, arginine, and serine (Sharma et al., 2023). Therefore, the potential of distillery by-products for protein recovery is well established, however further research is required to achieve the economical extraction.

3.1.2. Protein recovery from brewery by-products

Brewery by-products are mainly of three forms, i.e., brewer's spent grains (BSG), hot trub, and spent brewery's yeast. Among these, BSG is the predominant by-product, accounting for 85 % of the total by-products. The protein content of BSG lies in the range of 8.9–35.4 % (w/w on dry basis). Hot trub is the sediments formed during wort boiling, which is ~ 1–2 % of the total by-products. The hot trub contains 40–70 % (w/w on dry basis) protein. Moreover, spent brewer's yeast is the residual or surplus yeast accounting for ~ 15 % of total by-products with protein content of 40–60 % (w/w on dry basis) (Rodriguez et al., 2023). The study also reviewed various protein extraction methods from BSG and found that the pretreatment methods, viz., enzymatic, hydrothermal, ultrasound-assisted and microwave could be advantageous when applied prior to the popular extraction methods, i.e., ethanolic, alkali and enzymatic (Rodriguez et al., 2023). The protein composition of brewery by-product is also dependent on the source of by-product, crop species and determination method (Hejna, 2022). The protein recovery from BSG could be enhanced by using the combination of alkaline and acidic pretreatment. The BSG contains total amino acid of 3464.42 ± 0.09 nmol g^{-1} with an essential amino acid fraction of 2846.75 ± 0.04 nmol g^{-1} (Chetrariu et al., 2022). The major amino acids present in BSG were glutamic acid, 11307.93 ± 0.04 nmol g^{-1}; aspartic acid, 8802.8 ± 0.06 nmol g^{-1}; glutamine, 4172.62 ± 0.03 nmol g^{-1}; serine, 774.86 ± 0.05 nmol g^{-1} and proline, 697.96 ± 0.03 nmol g^{-1} (Chetrariu et al., 2022). Recently, tandem mass spectrometry coupled with liquid chromatography analysis of malt spent grain indicated the presence of amino acids, i.e., arginine, phenylalanine, valine, lysine, leucine, histidine, proline, threonine, and γ-aminobutyric acid (Di Matteo et al., 2023).

3.1.3. Protein recovery from winery by-products

The process of wine-making results in the generation of enormous quantities of by-products. The nature of waste generated is highly dependent on the vinification process, which alters the residual material's physico-chemical properties. The major wastes from winery industries are in the form of organic (grape pomace, seeds, pulp and skins, grape stems, and grape leaves) and inorganic (diatomaceous earth, bentonite clay, and perlite) wastes, along with wastewater, greenhouse gases and VOCs (volatile organic compounds). Grape pomace is a foremost winery waste originating throughout production and generally consists of 50–72 % moisture content. The insoluble residues of grape pomace have 16.8–24.2 % lignin along with 4 % protein. Moreover, grape seeds contain (w/w) fibre (40 %), essential oil (16 %), protein (11 %), and complex phenolic compounds (7 %), viz. tannins, along with sugars and minerals (Deng et al., 2011). Red grape pomace and lees contain significant protein concentration and could be used as protein-enriched feed. In a study, the crude protein content of an experimental diet containing 100 g kg^{-1} of red grape pomace and wine lees was evaluated and found to be 35.4 and 36.8 g 100 g^{-1}, respectively (Martínez-Antequera et al., 2023). The incorporation of winery protein-enriched waste as a supplement in feed showed improved physiological function of juvenile *Liza aurata*. Moreover, grape pomace can be used as a substrate for microbial protein production. It could serve as an alternative for protein-enriched animal feed as well as a potential source for human dietary needs (Kalli et al., 2018). Therefore, the bioconversion of grape pomace into microbial proteins could serve as a promising footstep in combating protein malnutrition worldwide.

3.2. Sugar recovery

Sugar is a form of carbohydrate that serves as an instant energy source to the human body (Fig. 3). Sugar occurs naturally in many foods, an integral part of our food habits. The body uses sugars and starches from carbohydrates to supply glucose to the brain and provide energy to cells around the body. However, sugar supplementation is not needed for the body as the amount required could be easily obtained from other sources, viz., fruits, vegetables, and dairy products. Rapidly increasing population, food scarcity, and changes in food habits have increased the sugar demand, which could be satisfied by sugar recovery from food industry waste (Fig. 3). A range of valuable reducing sugars and carbohydrate compounds, i.e., monosaccharides and oligosaccharides, can be produced from these waste (Zhang et al., 2020).

3.2.1. Sugar recovery from distillery by-products

Distilleries are among the most polluting industries, as 88 % of their raw materials are transformed into waste discarded in water bodies, causing water pollution. DSW (distillery spent wash) has been reported to be produced in substantial quantities and appears to have large values of BOD and COD. DSW is an unwanted dark brown-coloured liquid generated from a reboiler in the distillery with an obnoxious odour. On average, about 12–15 litres of DSW is produced per litre of alcohol (Shinde et al., 2020). Primarily, distillery by-products are used as fertilizer or animal feed. However, distillery stillage has a significant presence of melanoidins (condensation products of sugars and amino acids). Pot ale contains several reducing sugars, i.e., arabinose, galactose, glucose, rhamnose, and xylose in significant amounts, i.e., 119 ± 57.1, 46.2 ± 27.5, 283 ± 329, 7.58 ± 3.40 and 115 ± 37.2 g L^{-1}, respectively (Edwards et al., 2022).

However, the sugar recovery from distillery waste is in its infancy. This may be because distillery waste can be used to produce other valuable items, viz., butanol and methane (Wang et al., 2022). Thus, the researcher's primary focus is on enhancing the availability of sugar in distillery waste for the conversion of butanol or methane. Therefore, the economic recovery of sugar from distillery waste to be utilized as food and feed needs much further investigation.

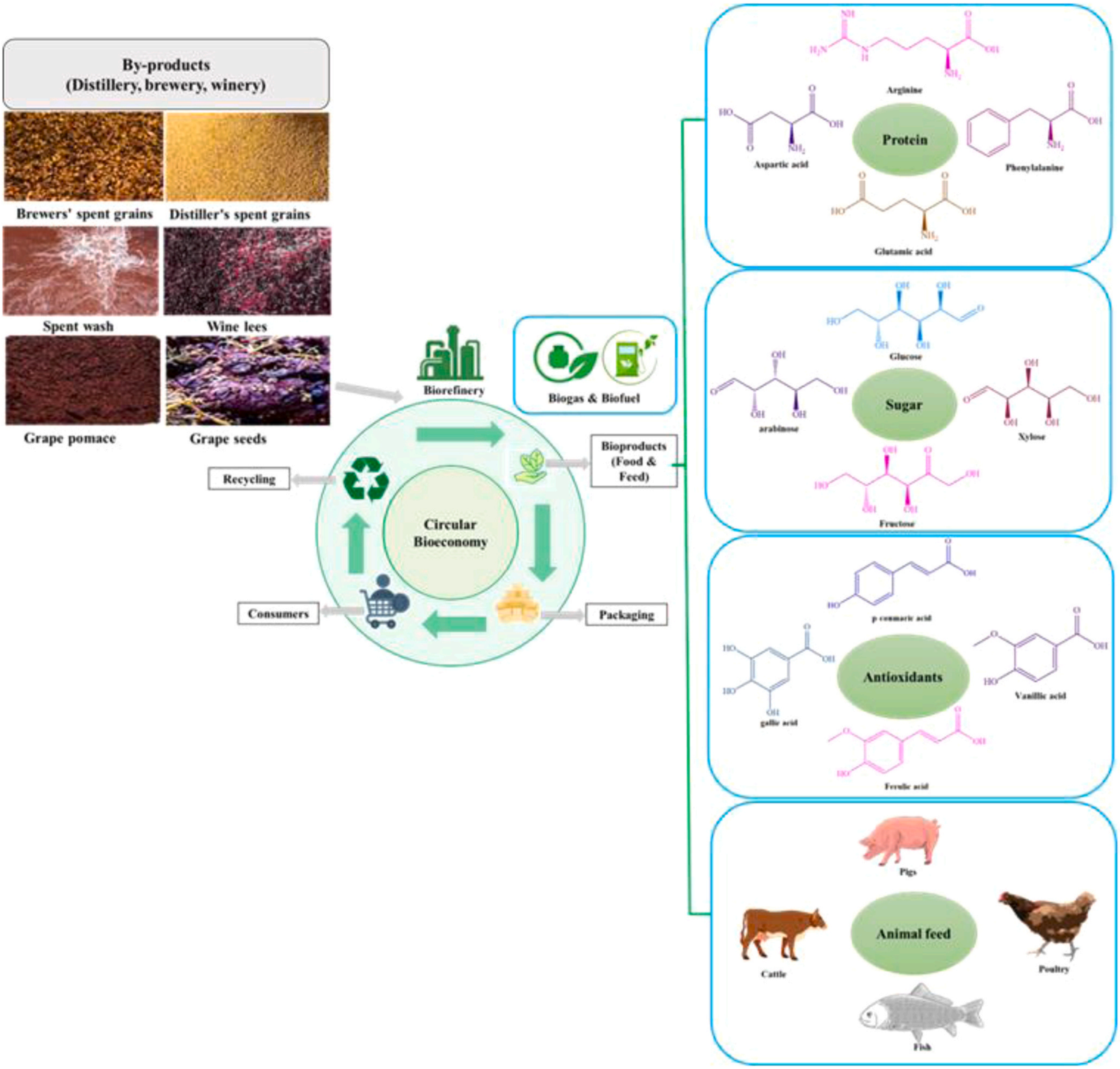

Fig. 3. Valorization of alcoholic beverage industry by-products for food, animal feed and energy recovery in circular bio-economy framework.

3.2.2. Sugar recovery from brewery by-products

BSG has high protein, sugar, minerals, and fibre content; mainly used as animal feed. Nowadays, attempts have been made to recover sugars from the BSG. It has a high moisture content of 70–80 % (w/w) along with the presence of fermentable sugars, i.e., cellulose and hemicellulose, which could be converted into glucose, xylose, arabinose, mannose, and galactose. Therefore, BSG could be considered an ideal substrate for microbial cultivation and fermentation (Rachwał et al., 2020). Semi-continuous subcritical water hydrolysis of BSG has resulted in a maximum yield of reducing and total reducing sugar, i.e., 6.4 g and 38.3 g 100 g^{-1} of BSG, respectively (Torres-Mayanga et al., 2019). The study observed a remarkable level of arabinose (3.13 ± 0.13 g 100 g^{-1} of BSG) at 160 °C along with a significant concentration of other sugars, viz., galactose, glucose, xylose, fructose, and sucrose at elevated hydrolysis temperatures. Under the optimal operating condition of subcritical water technology (210 °C, 20 mL min^{-1} water flow rate, and S/F of 64), the maximum yield of reducing sugars produced was 5.84 g 100 g^{-1} of feed, and the maximum total reducing sugars yield was 35.11 g 100 g^{-1} of feed (Torres-Mayanga et al., 2019). Similarly, a comparative study was conducted to analyze the effect of subcritical water hydrolysis by using a single reactor and sequential reactors on reducing sugars as well as total reducing sugar concentration in BSG (Eduardo et al., 2022). The study reported a notably higher release of monosaccharides employing a single reactor (47.76 mg g^{-1} carbohydrates at 180 °C). The hydrolyzate thus obtained has been observed to have notable levels of xylose and arabinose (0.477 and 1.039 mg mL^{-1}).

The application of sonication for the pretreatment of BSG could enhance the reducing sugar yield up to 2.1-fold (from 151.1 ± 10–325 ± 6 mg g^{-1} of biomass) under the optimum conditions, i.e., 20 % of ultrasound, 26.3 °C, 60 min and 17.3 % (w/v) biomass (Hassan et al., 2020). The extraction of sugar from BSG could also be improved by employing deproteinization followed by acid-catalysed steam explosion. The deproteinized BSG following steam explosion treatment showed the ~ 49.8 % recovery of xylose under the optimum conditions (173.5 °C for

15.5 min and catalyzed with 0.5 % w/v H_2SO_4) along with substantial recovery of xylose (30 %) and arabinose (93 %) (Rojas-p and Narv, 2022). The study also reported 72.2 % recovery of glucose following enzymatic hydrolysis (Cellic® CTec2: Novozymes) at 15 % of PFU substrate g^{-1}. Therefore, the sugar recoveries from BSG have shown potential and attempts should be made for the commercial scale production in the near future.

3.2.3. Sugar recovery from winery by-products

The sugar content of pomace differs based on its form, i.e., commonly of white and red skin color. White grape pomace predominates soluble dietary fibers, whereas red is rich in insoluble dietary fibers. These dietary fibers consist of a range of sugars, i.e., glucose, xylose, galactose, arabinose, and mannose—the grape varieties, viz. Cabernet sauvignon, Merlot, Morio muscat, Muller Thurgau and Pinot noir contain a significant amount of glucose in the insoluble dietary fibers in the range of 3–9 % (Deng et al., 2011).

The literature survey of recent studies on the recuperation of sugars from grape pomace and seeds showed enormous potential of subcritical water hydrolysis (Pedras et al., 2020). A recent study showed a positive effect on subcritical water hydrolysis of grape pomace using semi-continuous flow through by pH and temperature regulation (Eduardo et al., 2023). The study observed the highest sugar concentration (34.64 ± 6.16 g 100 g^{-1}) under optimum levels of pH (6.0) and temperature (150 °C). The study also detected the presence of other sugars, i.e., cellobiose, glucose, fructose, and arabinose by using Benitaka's grape pomace, in which the solvent-to-feed ratio was 30 g water g^{-1} grape pomace. Under the optimum condition of pH and temperature, the concentration (in g 100 g^{-1}) of cellobiose, glucose, fructose, and arabinose observed were 7.04 ± 1.25, 4.77 ± 0.87, 19.36 ± 3.58, and 3.45 ± 6.16, respectively (Eduardo et al., 2023). Further, the sugar content in the grape pomace can also be utilized to generate value-added phenolic compounds by employing microbial fermentation. Recently, solid-state fermentation of grape pomace was carried out by using *Rhizopus oryzae*, which converted grape pomace into phenolic compounds with reduction in the sugar content following fermentation (Šelo et al., 2023). Cost-effective process development would be needed to popularize the sugar recovery from winery products. Hence, more investigation is required to recover sugars from the winery by-products economically.

3.3. Antioxidant recovery

Antioxidants are molecules that prevent cellular damage by neutralizing free radicals and providing them with electrons. The antioxidant actions include diverse reactions, i.e., radical scavengers, hydrogen donors, electron donors, peroxide decomposers, singlet oxygen quenchers, enzyme inhibitors, synergists, and metal-chelating agents (Gulcin, 2020). The interaction of low MW antioxidants with free radicals can impede the series of reactions from damaging crucial molecules. It can stabilize the highly reactive pro-oxidants that accumulate to induce oxidative stress, hence imparting protection against oxidative damage. Some of these antioxidants, viz. glutathione, ubiquinol, and uric acid, are formed during regular metabolism, while other, less potent antioxidants are consumed through food. Antioxidants primarily involved in scavenging the free radicals in the body, viz., vitamin E (tocopherol), vitamin C (ascorbic acid), β-carotene should be supplemented through diet. Antioxidants have been extracted from several plants, animals, and microorganisms as well as from industrial processes by-products (Table 2b). However, their extraction and purification processes are cost-intensive, which can be made economical by using industrial waste from breweries, wineries, and distilleries as the potential raw materials (Fig. 3) (Chandimali et al., 2025).

3.3.1. Antioxidants recovery from distillery by-products

Distillery by-products contain a wide range of antioxidant compounds. There are several studies present in the literature for the extraction of antioxidants from distillery wastes. Phenolic compounds

Table 2b
Extraction methods and concentration of antioxidants from distillery, brewery and winery by-products.

By-product	Extraction method	Antioxidants	Concentration	Reference
Brewers' spent grains	Ultrasound-assisted extraction (80 °C, 50 min, and 65:35 % ethanol: water)	Total phenolics Ferulic acid Vanillic acid p-coumaric acid	4.1 ± 0.1 mg GAE g^{-1} DW 1.5 ± 0.2 mg L^{-1} 0.78 ± 0.18 mg L^{-1} 0.12 ± 0.23 mg L^{-1}	(Iadecola et al., 2022)
Brewers' lees	Solid-liquid ectraction (water 1:10 w/v, homogenization at 60 °C for 2.5 hr under constant stirring)	Total phenolics Gallic acid Hydroxyphenyl acetate Epicatechin Sinapic acid	10.339 ± 0.195 mg GAE g^{-1} 8.712 ± 1.234 mg g^{-1} DM 20.606 ± 2.885 mg g^{-1} DM 5.344 ± 0.299 mg g^{-1} DM 14.279 ± 3.372 mg g^{-1} DM	(Petrón et al., 2021)
Distillery stillage	Microwave assisted extraction (3 min, 80 % ethanol or 80 % methanol)	Polyphenols p-coumaric acid Ferulic acid	5.07 ± 0.03 mg GAE g^{-1} DM 23–25 % 42–48 %	(Mikucka, et al., 2022a)
Distillery stillage	Subcritical water extraction (30-min SWE with a solid-to-solvent ratio of 1:15 140 °C)	Total phenolics Ferulic acid p-coumaric acid	4.88 ± 0.16 mg GAE g^{-1} DM 29–32 % 20–24 %	(Mikucka, et al., 2022b)
Winery grape skins	Surfactant (tween 20) based extraction (10 mM Tween20/30 % ethanol, followed by 60 % ethanol)	Anthocyanins Other phenolics	49.3 % 52.3 %	(Carullo et al., 2022)
Winery grape stems	Hydroethanolic extraction (ethanol:water 50:50 v/v)	Total phenolics in: Verdelho (white stem) Tinta roriz (red stem) Ortho-diphenols in: Verdelho (white stem) Malvasia fina (white stem)	64.43 ± 1.34 mg GAE g^{-1} DW 64.73 ± 1.40 mg GAE g^{-1} DW 55.73 ± 0.68 mg GAE g^{-1} DW 58.93 ± 4.17 mg GAE g^{-1} DW	(Costa et al., 2023)

DM: dry matter; DW: dry weight, GAE: gallic acid equivalent with antioxidant activity can be extracted from spent grain by using either of the two popular processes US (ultrasound-assisted) and UT (Ultra-Turrax) (Chetrariu and Dabija, 2021). The highest total phenolic amount reported in this research was 1.76 and 2.11 mg GAE (gallic acid equivalent) g^{-1} spent grain dry weight (DW) for UT and US pretreatment conditions, respectively. The study also observed maximum flavonoid content of 1.67 and 1.63 mg QE (quercetin equivalents) g^{-1} spent grain DW for UT and US pretreatment, respectively. DPPH (2,2-diphenyl–2-picrylhydrazyl) free radical scavenging assay was employed for antioxidant quantification; it showed a range of values for UT (25.88 %–79.58 %) and US (27.49 %–78.30 %). The phenolic compounds detected were p-coumaric acid (20.4 ± 1.72 and 14.0 ± 1.14 mg 100 spent grain^{-1} DW for UT and US), rosmarinic (6.5 ± 0.96 and 4.0 ± 0.76 mg 100 spent grain $^{-1}$ DW for UT and US), chlorogenic (5.4 ± 1.1 mg 100 spent grain^{-1} DW for UT and nondetectable for US), and vanillic acids (3.1 ± 0.8 and 10.0 ± 1.03 mg 100 spent grain^{-1} DW for UT and US) (Chetrariu and Dabija, 2021).

Another study utilized a combination of forward osmosis, resin (XAD16) adsorption and AD to recover antioxidants viz. melanoidins and polyphenols, water and biogas from distillery wastewater and achieved recovery of polyphenol (91 %), melanoidins (72 %), water (72 %) along with methane yield of 189 mL g^{-1} VS_{in} (volatile solid content) (Singh et al., 2020). In this study, the forward osmosis step had a flow rate of 1 L min^{-1} with a draw solution concentration of 3 M $MgCl_2.6H_2O$.

The recovery of antioxidant compounds from distillery stillage was performed by using different extraction methods viz. conventional solid-liquid extraction, microwave-assisted, and ultrasound-assisted by Mikucka et al. (2022c). The study reported the uppermost yields of total polyphenol, i.e., 3.73 mg GAE g^{-1} and phenolic acid concentration of 2.51 µg g^{-1} (microwave assisted extraction, 8 min and ethanol (70 %). The study also illustrated a significant presence of ferulic (~ 0.80 µg g^{-1}) and p-coumaric (~ 0.72 µg g^{-1}) acids. The recent research in the field suggested that the microwave-assisted extraction method is superior over other extraction methods in terms of antioxidant yield and process simplicity. Therefore, the microwave extraction of antioxidant from distillery by-products could be useful in developing a potent extraction process.

3.3.2. Antioxidants recovery from brewery by-products

The most abundant by-product of the brewery industry is BSG, which is 85 % of the total generated by-products. The exploration of potential applications of BSG as human food to increase health benefits is gaining a lot of attention because of the richness in bioactive phenolic compounds that have antioxidant activity. The antioxidants from BSG can be recovered by various extraction methods, viz., solid-liquid, microwave-assisted, enzymatic and alkaline reactions (Chetrariu and Dabija, 2021). On studying the efficiency of diverse solvents, viz., NaOH (0.75 %), acetone (50 %), MeOH (50 %), MiliQ water, and MeOH + 0.3 % HCL for the extraction of polyphenol from BSG and brewer's spent hops (BSH), it was found that NaOH is the best solvent for the extraction (Codina-Torrella et al., 2021). The study proposed 1.45 % NaOH and 80 °C as the optimum conditions for the extraction of polyphenol. Derived optimum conditions have led to the extraction of 24.84–38.33 µmol GAE g^{-1} polyphenol from BSG and 24.84 ± 1.55 µmol GAE g^{-1} from BSH. The main antioxidant extracted from BSG was ferulic acid (156.55–290.88 mg 100 g^{-1}). Another study evaluated different by-products of malt and beer for their *in vitro* antioxidant potential by using keratinocyte cell cultures, and highest yields of phenolic compounds (12.9 mg GAE g^{-1}) were found in the caramalt malt extract (Almendinger et al., 2020). The study reported that using the caramalt malt extract at a concentration of 0.5–1 % could inhibit tyrosinase activity by 78 and 87 %, respectively. As tyrosinase is a crucial enzyme in skin pigment formation, the inhibiting activity of caramalt extract could be used in cosmetic products to reduce the melanin content in the skin. In a similar type of study, the bioactivity of spent products of malt, hop, and yeast was evaluated *in vitro* on the keratinocytes HaCaT cells, and it was observed that spent hop and yeast extracts could thwart oxidative stress by improving the mitochondrial activity (Censi et al., 2021). The *in vitro* antioxidant potential of these by-products was evaluated using their extract, and it was found that the BGS with a higher content of baked malt had lesser DPPH, $ABTS^{+\cdot}$ and TPC values. Therefore, the aqueous extracts from brewery by-products could be a promising source for antioxidants. However, further studies are needed to clarify the antioxidants and phenolic profile as well as effect of use on health in long term.

3.3.3. Antioxidants recovery from winery by-products

The prime winery by-product is grape pomace that includes peel, seed, stem, and pulp. Grape pomace contains a wide range of phenolic compounds and flavonoids. The phenolic compounds from grape pomace could be extracted using conventional methods, viz., soxhlet extraction, hydrodistillation, solid-liquid extraction, and solvent-based extraction. However, modern techniques, i.e., superficial fluid extraction, pulsed ohmic heating, microwave-assisted extraction, liquified gas technology, ultrasound, pulsed electric fields, high voltage electrical discharges, etc., have shown improved extraction of antioxidants from winery by-products (Aresta et al., 2020; Kumar and Surendra, 2022). These modern techniques could also help to achieve green extraction alternatives for the phenolic compounds from winery by-products.

Moreover, the integrated application of modern techniques has shown an augmentation in antioxidant recovery levels. A study reported anthocyanin recovery using combined extraction technology of ohmic heating with food-grade solvents (Coelho et al., 2021). Research has reported a similar total phenolic content of 3.28 ± 0.46 mg g^{-1} DW GAE for ohmic heating compared to conventional extraction (2.84 ± 0.037 mg g^{-1} DW GAE). The study observed the same trend for antioxidant capacity, as the conventional process exhibited antioxidant activity and ohmic heating of 2.02 ± 0.007 and 2.34 ± 0.066 g 100 g^{-1} ascorbic acid equivalent, correspondingly. The study reported cyanidin–3-O-glucoside, delphinidin-3-O-glucoside, malvidin-3-O-acetylglucoside, petunidine-3-O-glucoside, and peonidine-3-O-glucoside as the major anthocyanins (Coelho et al., 2021). The seed extracts from the winery by-products showed better antioxidant activity than other parts, i.e., skin and stems (Silva et al., 2018). Antioxidant activity (ATBS) reported for seeds from *Touriga nacional* and *Preto martinho* varieties were 185.2 ± 5.9 and 206.3 ± 7.7 µmol Trolox g^{-1}, respectively. The literature showed that there have been many successful studies on the extraction of antioxidants from winery by-products. However, scaling up the processes on an industrial scale has yet to be achieved.

3.4. Animal feed recovery

Animal feed refers to raw or processed product (complete feed, concentrated feed, feed additives, traditional feed) given to domesticated animals The food processing industry's wastes are by and large nutritious and can be utilized for generation of safe animal feed ingredients employing contemporary processes and technologies which enabled their inclusion into animal diet without compromising the growth and performance (Rajeh et al., 2021). One of the foremost concerns of the present world is the food-feed competition. The rapidly increasing human population has heavily impacted plants and animal products. Reports suggested that 60–70 % rise is expected in the global need for animal products by 2050, exerting tremendous pressure on rearing animals and requiring more animal feed. Currently, one-third of total cereal production (~800 million tonnes of cereals) is used in animal feed, which is projected to reach up to 1.1 billion tonnes by 2050 (Makkar, 2018). It would create an imbalance in food and feed and could further exacerbate food insecurity in the world. Therefore, exploitation of alcoholic beverage industry by-products (Fig. 3) as animal feed presents a sustainable solution towards concurrent waste management and food security with diminished need for growing conventional feed.

3.4.1. Animal feed recovery from distillery by-products

The distillery by-products mainly contain wet grains and thin stillage. Wet grains can either be dried to make dry distillers' grain or given straight to cattle, whereas the thin stillage could be dried to create condensed distillers solubles or utilized as high-moisture feed. Distillers' grains can be used to enhance the growth performance and nutritional profile in mealworms rearing (Zhang et al., 2019). The study observed growth performance (53–67 % of control), feed conversion (36–45 % of control) and utilization ration (50–57 % of control), while reared on spirit distillers' grains in term of mealworms DWs. After 60 days of mealworm rearing on spirit distillers' grains, the crude protein, and crude fat content (%) change from 13.87 ± 0.36–70.10 ± 0.63 and 6.85 ± 0.35–11.95 ± 0.45, respectively.

Similarly, the fish meal substitution with protein-enriched distillers dried grains (25 %) was found to be acceptable for growth and feed utilization in the cultivation of *Pangasianodon hypophthalmus* (Allam et al., 2020). Another study attempted to replace 44 % of conventional feeds for light lambs with by-products concentrate containing 18 % distillers' dried grains with solubles, 18 % dried citrus pulp, and 8 % exhausted olive cake (de Evan et al., 2020). The results of the study suggested that the meat and subcutaneous fat from lambs fed on by-product concentrate had higher polyunsaturated fatty acid content, along with better n-6/n-3 fatty acids. Similarly, the distillers' grains with solubles can be used as a supplement to feed boiler chicken. However, natural contamination of distillers' grains with deoxynivalenol could negatively affect the growth of the boiler chickens (Kim et al., 2021). Therefore, using a specific percentage of distillery by-products as animal feed is advisable due to their rich protein content. Vigorous research is required to achieve the proper utilization and improved benefits of distillery by-products as feed.

3.4.2. Animal feed recovery from brewery by-products

The rich content of sugars and proteins in BSG offers an enormous potential to be used as animal feed. Currently, BSG is mainly used as cattle feed, where it can be utilized directly in wet form or as dry matter (DM). Apart from cattle, BSG is also used as feed for poultry, pigs, and fish (Mussatto, 2014; Negash, 2021). A study was conducted to evaluate the effect of partial replacement of fishmeal by BSG and yeast for *Sparus aurata* and *Oncorhyncus mykiss* fishes (Nazzaro et al., 2021). The results advocated the use of brewery by-products for fish cultivation as the inclusion of 20–30 % of BSG and spent yeast in the feed for both the fish showed similar results compared to a feed with fish meal. Another study evaluated the possibility of partially substituting *Cuiabana sausage* pork by brewery by-product flours (Campos et al., 2021). The study suggested that the brewery by-product flours concentration could affect sausage colouration, with decreased luminosity, L*: 52.060 in the 6 % (w/w) treatment compared to the 0 % treatment controls (L*: 63.956), whereas the titratable acidity exhibited higher (1.162 g 100 g^{-1}) compared to the 0 % treatment control (1.093 g 100 g^{-1}) of lactic acid. Further, protein content and total enzymatic fibres were augmented to 19.068 and 9.233 g 100 g^{-1} of samples, correspondingly. Similarly, BSG and spent yeast were found to an ideal feed protein supplement source for the cultivation of *Sparus aurata* (Estévez et al., 2021). The study suggested that the addition of spent yeast (30 %) and BSG (15 %) in the *S. aurata* feed produced comparable results for growth, food conversion and fillet final composition to a feed with fish meal. Its application as the key protein source reflected improved protein digestibility (89–95 %). The BSG and spent yeast can also be utilized as the main protein source in the *Oncorhynchus mykiss* feed (Estévez et al., 2022). The addition of 20 % spent yeast and 15 % BSG in feed, along with 15 % fish meal showed parallel growth with a protein digestibility of 87–89 %. Therefore, the potential of brewery by-products as animal feed is comprehensible; however the percentage of brewery by-product in feed needs to be explored for different animals.

3.4.3. Animal feed recovery from winery by-products

The most common winery by-product is grape pomace, which constitutes 20–25 % of the grape weight and contains skin, seeds, and other solid parts. It contains proteins, dietary fibers, lignin, polyphenols, and fats, mainly used as feed for ruminants and rabbits (Ferrer-Gallego and Silva, 2022). The grape pomace from red wine by-product can be used as feed for sheep due to its significant polyphenol and polyunsaturated fatty acid content, resulting in improved meat and milk quality (Guerra-Rivas et al., 2017). This might be attributed to the lower lignified fibre, better digestibility, and enhanced polyphenol content in pulp compared to the seeds. The study also suggested that the nutritional value of grape pomace from red wine is inconsistent and reliant on the proportion of seeds and pulp. A study explored the possibility of using the volatile content of winery by-products as a supplement to raise fish diets' nutritional value and organoleptic qualities (Câmara et al., 2020). The results of the study suggested presence of 153 volatile organic compounds of diverse chemical families (esters (36), carbonyl compounds (31), alcohols (20), terpenoids (18), acids (17), furanic compounds (11), volatile phenols (04), lactones (02) and miscellaneous (14). The presence of these compounds from winery remains in the feed could improve the aroma and bioactivity of aquafeed. Similarly, including grape pomace with feed as a supplement could improve the growth, immune status, and metabolism of *Liza aurata and provide* protection against moderate hypoxia stress. The study observed enhanced feed efficiency and better metabolic and immunological status of the fish (Martínez-Antequera et al., 2023). The literature suggests that the winery by-products have enormous potential to improve animal feed. Therefore, more investigation is required to improve the quality of animal feed on an industrial scale.

3.5. Biogas recovery from the alcoholic industry by-products

Biogas recovery from distillery, brewery, and winery by-products is a promising and sustainable solution that addresses both environmental concerns and energy needs (Nagarajan and Ranade, 2020). Distillery by-products, i.e., spent wash or vinasse, are rich in organic matter and have high chemical oxygen demand levels, making them ideal substrates for biogas production (Iltchenco et al., 2020). Brewery by-products, viz. spent grains and yeast slurry, along with winery by-products, like pomace and grape stems, also possess significant organic content, further enhancing the potential for biogas generation (Buitrón et al., 2019) (Table 3). AD is the core process of biogas recovery, entails the disintegration of organic matter by microorganisms under anaerobic conditions. The benefits of biogas recovery from distillery, brewery, and winery by-products are multifold. Firstly, it provides an eco-friendly alternative to traditional fossil fuels, reducing greenhouse gas emissions and mitigating climate change (Shen et al., 2021). By capturing methane, a potent greenhouse gas, biogas production prevents its release into the atmosphere, thus curbing its impact on global warming. Additionally, the biogas process effectively treats and reduces the organic load in the by-products, resulting in a significant decrease in environmental pollution caused by the disposal of these wastes. Instead of releasing untreated or partially treated effluents into water bodies, which can lead to water pollution and eutrophication, the AD process offers a more sustainable approach.

Distillery by-products like draff, thin stillage, and syrup were examined by Kang et al. (2022) by incorporating acid pretreatment. Results showed that the acid pretreatment at lab scale bioreactor helped to reduce the digestion time and 68 % energy conversion from thin stillage. However, out of all by-products, syrup showed maximum methane yield of 545 L/kg VS. Jackson et al. (2020) tested mesophilic and thermophilic conditions for AD of distillery by-products. The results have been illustrated that while acetate oxidation was the dominant pathway at mesophilic temperature, hydrogenotrophic was the leading pathway at thermophilic conditions. The other pretreatment technologies were also applied to distillery by-products. Nagarajan and Ranade

Table 3
Biogas and biomethane recovery from brewery, distillery, and winery by-products.

Feedstock	Processing condition	Pretreatment of feedstock/addition	Inoculum	Maximum gas yield	Key findings and remarks	References
Distillery						
Draff, thin stillage and thick stillage, syrup	650 mL batch bottles, at 37 °C for 41 days	Acid pretreatment (1 % H_2SO_4 at 135 °C for 15 min)		545 L kg^{-1} VS from syrup	• Acid pretreatment helped to reduce the digestion time of solid by-products significantly • Stillage showed 68 % energy conversion as compared to draff (54 %)	(Kang et al., 2022)
Whisky by-products	650 mL batch bottles, at 37 °C and 55 °C for 30 days	Steam and acid pretreatment (2 % v/v H_2SO_4)		389 L kg^{-1} VS at mesophilic condition	• Acid pretreatment helped to accelerate the mesophilic biogas production. • At thermophilic condition, excess ammonia hindered the methane yield. • Hydrogenotrophic methane generation reported as dominant pathway.	(Kang et al., 2021)
whiskey distillery by-product	5 L lab scale CSTR at 37 and 55 °C		Mesophilic inoculum was collected from food waste AD plant while thermophilic was from pig slurry waste AD digester	Specific methane yield of 365 and 330 L kg^{-1}	• Acetate oxidation found to be important for methanogenesis in mesophilic AD • Hydrogenotrophic methane generation reported as dominant pathway in thermophilic condition. • Neutralization of liquid fraction of feedstock may require for enhanced methane production.	(Jackson et al., 2020)
Distillery spent wash	Batch bottles at 41 °C for 29 days.	Hydrodynamic cavitation pretreatment (capacity of cavitation device was 1.2 m^3/h		162 L kg^{-1} VS	• 14 % increment was observed in cumulative methane yield. • 1 GJ/ ton of COD was the net energy gain form the biomethane generated from spent wash. • Inlet pressure of 56 psi and 2 passes was found to enhance methane yield by 14 %	(Nagarajan and Ranade, 2020)
Distillery wash water	Glass reactor of 2 L for 25 days	Catalytic wet oxidation process (1 h at 175 °C and 0.69 MPa)		1.1 m^3 of biogas per m^3 of wash water	• BOD_5/COD value increased to 0.45 from 0.2 along with 73 % reduction in COD using catalytic wet oxidation. • 69 % of the methane was observed after the pretreatment.	(Bhoite and Vaidya, 2018a)
Distillery wash water	Glass reactor of 2 L for 25 days at 30 °C	Iron catalysed wet oxidation (Fe_2O_3 and Fe/ Activated carbon; T = 175 °C, P_{O2} = 0.69 MPa, loading = 33 mg/L)		1.2 m^3 of biogas per m^3 of wash water	• 87 % of COD conversion was observed after pretreatment. • 72 % of the methane was observed after the pretreatment. • 97 % COD was removed after combining the aerobic treatment.	(Bhoite and Vaidya, 2018b)
Liquid waste of gin distillation	Lab UASB bioreactor (1.3 L at 36 °C)			8.4 m^3 CH_4 m^{-3} d^{-1}	• Alkalinity and nutrient provided by swine wastewater co-substrate. • OLR of 28.5 kg COD/m^3/d was observed as optimum loading. • Over acidification was observed at OLR of 32 kg COD/m^3/d.	(Montes et al., 2019)
Vinasse	610 mL batch bioreactors (4 feedstock to inoculum ratio) for 14 days		Effluent from sludge	59 mmol CH_4 L^{-1}	• Highest methane yield was observed at 1.5 feedstock to inoculum ratio. • *Methanosaeta*, *Methanobacterium* and *Methanomassiliicoccaceae* OUT *vadinCA11* were the abundant archaeal community.	(Iltchenco et al., 2020b)
Pot ale		Alkaline ultrasonic pretreatment	Effluent from anaerobic digester running on food waste	333 L kg^{-1} VS	• Pretreatment helped to achieve significantly higher hydrolysis rate. • Anaerobic biodegradability of pot ale was increased by 34 % after pretreatment	(Gunes et al., 2021)
Winery						
Winery wastewater	2-stage CSTR (1 and 0.6 L for fiest stage and 7 and 4 L for second)		Anaerobic granular sludge used for the inoculation (12.4 g VS/L	7.1 Nm^3 CH_4 m^{-3} d^{-1}	• Higher acetic acid production was observed above 120 kg COD/m^3/ d at first stage. • Thermophilic condition ensured higher methane yield and close to theoretical one. • Lower feeding frequency increased the methane yield at thermophilic temperature.	(Vital-Jacome and Buitrón, 2021)

(continued on next page)

Table 3 (*continued*)

Feedstock	Processing condition	Pretreatment of feedstock/addition	Inoculum	Maximum gas yield	Key findings and remarks	References
Distillery						
Vine lees	500 mL of batch bottles at 35 °C		Effluent from sludge-abased digester	876 L kg^{-1} VS	• Techno-economic analysis showed that solid waste generated at winery may be able to replace the energy demand of winery. • Wine lees can produce up to 153,738 m^3/y of biogas	(Montalvo et al., 2020)
Winery wastewater	300 mL of batch bottles at 35 °C	Fly ash as source of iron (100 mg/L)	Effluent from sludge-abased digester	218 L CH_4 Kg^{-1} VSS^{-1}	• Addition of fly ash above 150 mg/L reduced the biogas production by 55 %. • 100 mg/L of fly ash helped to increased methane yield by 79 %.	(Lauzurique et al., 2022)
Winery effluent	2 stage CSTR (1 and 7.5 L volume for stage 1 and 2 working at 250 and 150 rpm)		Anaerobic granular sludge used for the inoculation	5.5 m^3 CH_4 m^{-3} d^{-1}	• Up to 26 kg COD/m^3/d was effectively treated in the 2-stage reactor. • It was observed that 220 g COD/L can be treated using two-stage reactor. Organic matter removal was 97 % of the initial concentration.	(Buitrón et al., 2019)
Brewery						
Brewer's spent grain	6.8 L CSTR at 35 °C and	Ultrasonic pretreatment at 800 W and 19 Hz frequency	-	107 L kg^{-1} TS	• Maximum methane content observed was 56 % after ultrasound pretreatment • AD of spent grain could generate 0.23 MWh and 1200 MJ of electrical and thermal energy respectively form 1 tonne.	(Buller et al., 2022)
Brewer's spent grain	250 mL of batch bottles at 35 °C	-	-	82 m^3 CH_4 t^{-1} DM	• Biogenic CO_2 generated during anaerobic digestion can fulfil 76 % of its requirement for brewing • Techno-economic analysis showed a potential reduction of US $ 116 million in cost incurred in CO_2 purchase.	(Lins et al., 2023)
Brewer's spent grain, defatted spent grain	500 mL of batch bottles at 35 °C	-	Effluent from full scale anaerobic bioreactor treating wastewater	379 mL g^{-1} dry matter	• Spent grain could potentially produce up to 7 million MJ of energy per year for Europe if fully utilized.	(Kavalopoulos et al., 2021)
Brewer's spent grain	120 mL of batch bottles at 35 °C	Thermal treatment (80 °C, 10 min)	Sewage sludge from UASB reactor	302 NL CH_4 kg^{-1} COD	• 1.71 MJ and 0.392 kWh of thermal and electrical energy can be generated per kg of dry spent grain. • Two stage pretreatment is an attractive technology for extracting sugar and biogas from spent grains.	(de Camargos et al., 2021)
Brewery wastewater	34 L two stage bioreactor,	Biomass encapsulation using alginate	Anaerobic digester sludge	2.3 L CH_4 day^{-1}	• Alginate encapsulation of anaerobic microbes helped in starting anaerobic process rapidly • Some washout was observed from encapsulated microbial biomass	(Chen et al., 2022)
Brewery spent grain and wastewater	250 mL of batch bottles at 35 °C	-	Anaerobic wastewater sludge	88 L kg^{-1} VS	• The biomethane showed potential of saving 0.114 kg CO_2/kg VS if used to produce electricity. • Acetoclastic pathway was dominant in the anaerobic digestion process	(Sganzerla et al., 2023)

(2020) performed hydrodynamic cavitation pretreatment on distillery spent wash. The results showed that the net energy that could be gained from the distillery spent wash was 1 GJ per tonne of COD. Bhoite and Vaidya (2018a) employed catalytic wet oxidation on distillery spent wash and reported a 73 % reduction in COD along with a maximum of 69 % methane. In a further study on distillery spent wash, Bhoite and Vaidya, (2018b) reported that iron-catalyzed wet oxidation helped to achieve 87 % of COD conversion to methane, while the average methane content was 72 %.

The liquid fraction of distillery by-products is high in aqueous ammonia and low in pH, and it is imperative to employ high-rate anaerobic bioreactors for these waste streams (Hackula et al., 2023). Montes et al. (2019) examined liquid waste from gin distillation in a lab scale-up flow anaerobic sludge blanket (UASB) bioreactor. Due to the low pH of liquid waste, co-feedstock (swine wastewater) was added to provide buffering capacity to UASB bioreactor. Experimental results showed that the UASB was able to handle up to 28 kg COD/m^3/d of organic loading rate and over-acidification occurred above 32 kg COD/m^3/d. The average methane yield observed was 8.4 m^3/m^3/d from UASB.

Brewers' spent grain is one of the main by-products of the brewery industry. The production and nutritional content of brewers' spent grain makes it a promising alternative for biogas generation (Kavalopoulos et al., 2021). Buller et al. (2022) stated that ultrasound pretreatment of spent grains could enhance the methane to 56 % in a continuous stirred tank reactor. Buller et al. (2022) also calculated and reported that employing 1 ton of spent grain in a continuous stirred tank reactor could produce 0.23 MWh of electrical energy.

Lins et al., (2023) performed a techno-economic assessment for Brazilian breweries to replace the commercial CO_2 with biogenic CO_2

from AD of brewers' spent grains. The authors reported that 76 % of CO_2 for brewing requirements can be fulfilled by utilizing all brewers' spent grain (2.3 million tonnes) as a source of methane and carbon dioxide. This would also save the cost of purchasing CO_2, which would otherwise cost US $ 116 million to breweries nationwide in Brazil.

Brewery wastewater is high-strength wastewater and rich in COD, which ranges between 2–14 gL^{-1} and could be used as a feedstock for biogas generation. It has been reported that for 1 litre of beer produced, around 10 litres of wastewater is generated (Olajire, 2020). Chen et al. (2022) anaerobically digested brewery wastewater using alginate encapsulation of microbial biomass in a two-stage bioreactor. The encapsulation of microbial biomass helped in the AD of high-strength brewery wastewater and 2.3 L of methane was obtained per day from the bioreactor. The encapsulation of microbial biomass also helped in the rapid start-up of the anaerobic process despite the strength of the wastewater.

3.6. Technological processing pathways for the alcoholic beverage industry

The technological processing pathways comprise a series of methods (physical, chemical and biological) applied to by-products for transforming them into value-added products. Generally, it includes pretreatment, initial processing, followed by secondary processing, and recovery of upcycled products. In the alcoholic beverage industry, the by-products are converted into animal feed, food ingredients, biogas and several other biomaterials. The technological processing pathways safeguard sustainable utilization of resources, environmental safety, and enhanced production within the context of the circular economy (Patel et al., 2018; Praveen and Brogi, 2025).

The alcoholic beverage industry's technological processing pathways embrace diverse treatment techniques and valorization methods, which have separate process flows and scale-up possibilities. The significant processing pathways for alcoholic beverage industries are AD, membrane treatment, thermal processing, and recovery of bioactive compounds (Constantin et al., 2024). Among them, the most significant and potential for scale-up is AD, which involves a pretreatment step prior to fermentation in an anaerobic reactor for biogas generation. Further, the remaining digestate can be utilized as fertilizer or soil additive (Yapıcıoğlu, 2025). The thermal processing entails evaporation and combustion processes to concentrate the liquid by-product of alcoholic beverage industry to obtain energy. Further, the potassium-rich ash could also be recovered and applied to the fields as soil amendments (Mikucka et al., 2022c). However, thermal processing routes have high energy demand and incurred cost as compared to AD. The technological processing pathways for the alcoholic beverage industry also encompass the extraction and/or recovery and purification of value-added bioactive compounds viz. proteins, polyphenols and other value-added compounds. The recovery process utilizes a variety of methods including solvent-based extraction, microwave or ultrasound-assisted extraction, or supercritical fluid, depending on the requirement and suitability for the extracted compound (Umego and Barry-Ryan, 2024; Kharayat et al., 2024; Mikucka et al., 2022b&c).

3.7. Circular Economy framework integration

The circular economy framework integration is the implication of circular economy principles into industrial production and extraction processes as well as in the supply and lifecycle of products. Therefore, to integrate the circular economy framework in the alcoholic beverage industry, the system should be efficient in recycling or repurposing the resources continuously with minimal waste generation and environmental impact. The alcoholic beverage industry by-products are redirected to recover value-added products viz. animal feed, energy, fertilizer and bioactive compounds in a circular manner with generation of no or minimal waste. Further, sustainable and recyclable product packaging could also help to minimize waste and put value in the chain. Therefore, the circular economy framework integration of the alcoholic beverage industry can contribute to achieving SDGs goals pertaining to SDG 7 and 12. Hence, the circular economy framework integration of the alcoholic beverage industry can provide a robust and sustainable production system through the continuous and recycled utilization of the by-products while reducing the waste generation with value augmentation (Mainardis et al., 2024; Gruba et al., 2022; Lopes et al., 2021).

Life cycle thinking (cradle-to-cradle): In the alcoholic beverage industry, the complete lifecycle evaluation of the products and by-products starts from the raw material or production (i.e., cradle), followed by utilization and resource recovery. Further, the recovered resource can valorize the waste by applying it as an input for a new production process. This led to closing the loop instead of going for final disposal, offering a cradle-to-cradle perspective. The cradle-to-cradle approach is based on the biodegradability or recyclability of the material that offers the possibility of new product development without losing significant quality and thus provides sustainable resource utilization along with minimum environmental impact. The application of recyclable material for packing could also support to achieve the SDG. In the alcoholic beverage industry, the cradle-to-cradle method promotes waste elimination by using resource recovery and recycling with support of the lifecycle assessment to evaluate environmental impact and sustainable production. Therefore, the production supports the various SDGs for improving economic, environmental and social sustainability (D'Ascenzo et al., 2024; Marrucci et al., 2024; Hospido et al., 2022).

Barriers to circular integration: Despite the advantages of circular integration, there are still some barriers that slow down the process of implantation of circular economy framework in the alcoholic beverage industry. These obstacles include technology, structure of organization/industry, economics, logistics and policy. In alcoholic beverage industries, the technical barriers lie in the inconsistency of by-product composition, unavailability of cost-effective technologies, challenges in the up gradation of existing processes and maintaining the quality and safety standards. The logistics barriers include problems in the storage and transportation of by-products due to their instability and widespread production sites that enhance complexity in processing and cost. Additionally, the economic barriers in the circular integration of the alcoholic beverage industry are the huge investment requirement and ambiguity of return on the investment due to inadequate market demand for the recycled products. There is also a lack of awareness and unavailability of adequate expertise at the organizational level in circular integration. Moreover, the policy-related barriers viz. paucity of supportive incentives and unclear policies and regulatory uncertainties also need to be addressed. There is also a need to encourage collaboration among industries to enhance the circular practices. Addressing the aforementioned obstacles enables effective circular integration within the alcoholic beverage business. (Lodhi, 2024; Dabija et al., 2024; Souza Piao et al., 2024).

3.8. Techno-economic analysis

The techno-economic analysis (TEA) has demonstrated its significance for the development process and subsequent scaling. TEA is a systematic approach consisting of both technical and economical parameters that offer the accurate assessment of performance, sustainability and feasibility of a process, product or technology. In the alcoholic beverage industries by-product circular economy integration, TEA offers the estimation of capital and operating costs along with the payback periods (Chai et al., 2022). AD system is widely used for valorization of by-products in the alcoholic beverage industry and has a significant contribution in capital cost depending on the scale and technology type. Substantial capital expenditures arise in the brewers and distilleries sector, specifically for an integrated water and waste treatment facility incorporating membrane filtering and a biogas capture system. The extent of investment could be increased by integration of an advance extraction or drying unit to valorize the spent grain. Further, operating expenses include maintenance, work force, and energy. In the recovery of bioactives, the operating cost would further increase due to the requirement of specialized chemicals and equipment. Moreover, the delay or more extended payback period also enhances the incurred cost of the product development from the alcoholic beverage industry by-products (Osman et al., 2024; Sganzerla et al., 2021).

The transformation of the Italian wine industry waste into valuable products is an ideal model for the involvement of the bio-economy principles. Valorization of winery leftovers with maintenance of environmental sustainability was achieved via incorporation of two side production chains in a circular way to produce grapeseed oil and tartrate. The lifecycle assessment of the study has illustrated that the most impacted categories were human carcinogenic toxicity, freshwater eutrophication, and fossil resource scarcity with normalized impacts of 9.22E−03, 3.89E−04, and 2.64E−04, respectively. The study observed a three times lower environmental impact in the circular system compared to the linear system (Ncube et al., 2021). Another case study was conducted for utilization of BSG in a biorefinery system in Brazil, in which a simulation process was performed through Aspen Plus that served as the basis for TEA and environmental assessment according to the regional conditions. The study was conducted with full mass and energy integration in configuration to the best economic and environmental performance. This case observed economic margin (62.25 %), potential environmental impact (0.012 PEI Kg^{-1} along with the carbon footprint of processing stage (0.96 kg CO_2-e Kg^{-1} of BSG) (Mussatto et al., 2013). Similarly, the TEA potential of bioenergy (electric and thermal) from the AD of vinasse and stillage was evaluated, and a methane production of 3.8×10^6 m^3 $year^{-1}$ was achieved in an integrated process (Tena et al., 2022). The study observed electricity and thermal energy generation of 14.61 GWh $year^{-1}$ and 1,37 × 105 GJ $year^{-1}$, correspondingly. Hence, the circular economy implementation can be augmented with the advancement in scaling, logistics, and collaboration at the regional and international levels.

3.9. Health and safety considerations

Using by-products from the alcoholic beverage industry requires careful consideration to safeguard the health and safety of workers, customers, and animals. These considerations offer a safe conversion of by-products into energy, food, animal feed, and other products with value-addition. Chemical safety and microbial contamination are the primary issues with these by-products. The by-products of the alcoholic beverage sector are prone to bacterial and fungal contamination, including *Salmonella*, *E. coli* and molds which can compromise food safety or cause spoilage if not appropriately handled and processed (Rot et al., 2025). Workspaces and equipment need to be cleaned and sanitized to reduce the chance of cross-contamination from chemicals, raw materials, or other intake streams. Additionally, routine testing should be performed for microbiological loads, handling, storage, and transportation procedures with appropriate and efficient sanitation (Zhu et al., 2024). Challenges about the appropriate use of chemicals and associated safety precautions are also present in the alcoholic beverage sector. The residues from solvents, cleaning agents, additives, and heavy metals can contaminate the by-products of the alcoholic industry. Recently, heavy metals (Cu, Cd, Pb, Cr, Fe and Zn) were found in Tanzania's most consumed brands through an atomic absorption spectrometer (Eliaza et al., 2024). The study reported increased levels of Fe and Cr compared to the WHO guidelines, suggesting a potential carcinogenic risk associated with the toxic metals. Toxic substances viz. methanol and acetaldehyde must be absent from these by-products in order to be utilized as food and animal feed. Preventing unintentional exposure and contamination during storage is also crucial. Consequently, there must be comprehensive emergency protocols and efficient safety measures for incidents such as chemical exposure, spills, and fire hazards (McCambridge and Lesch, 2024; Praveen and Brogi, 2025).

3.10. Future perspectives and policy recommendations

The alcoholic beverage industry generates a significant number of by-products that have the potential to be harnessed for food, energy, and animal feed (Fig. 4). The alcoholic beverage industries, particularly breweries and distilleries, generate substantial waste materials, i.e., spent grains, yeast, and distillation residues. These by-products often become waste and contribute to environmental pollution and resource wastage. The industry can significantly reduce its environmental footprint by recovering energy and valuable components from these by-products. Integrating the alcoholic beverage industry with the circular economy can enhance its utility. However, there are still some unaddressed challenges and a need to incorporate advancements. In the near future, the industry should aim to advance valorization technologies, such as green extraction methods, combining biorefineries and better recovery efficiency to ensure economic viability. Further, more robust techniques needs to be developed and adopted for lifecycle assessment and digitalization of the system to get real-time quality management. Efficient and economic production could be attained by alliance of facilities and infrastructure among the different stakeholders. Furthermore, there is also a need to adopt attractive and recyclable packaging to impart innovation in the circular process and maintain sustainable environmental practices.

The comprehensive integration of a circular economy within the alcoholic beverage industry necessitates substantial policy revision. The policy needs to be clear, consistent and should be of the same standard at the regional and international levels, so that the reuse of the by-products can be paced. The policy should also focus on subsidies and additional grants for circular technologies. Increased funding and greater autonomy should be allocated for research and development, including streamlined processes for the scaling of promising technologies. There is also a need to establish a standard for circular products as well as easy and effective certification schemes. Policy should be more centred on creating awareness and training programs to develop a better workforce and consumer base for the cyclic products from the by-products of the alcoholic beverage industries.

4. Conclusion

There are several by-products produced by the alcoholic beverage industries that can be transformed into value-added products. Spent grains, yeast, and distillation residues are among the significant waste products produced by these industries. These by-products enriched with nutrients and organic materials that make them valuable for the conversion to energy with recuperation of value-added products. Mostly, these by-products are discarded that causes serious damage to the environment. Therefore, by recovering energy and valuable components from these by-products, the industry may significantly reduce its environmental impact. AD and combustion processes can be effectively used to produce energy from organic materials present in spent grains and distillation residues. It can provide a renewable energy source while reducing the industry's reliance on fossil fuels. The industry can also become more self-sufficient and sustainable by using the energy generated to power its own production processes. It lessens the environmental effect of the industry and encourages the growth of renewable energy. Spent grains, a by-product of brewing, are considered a valuable livestock nutritional resource loaded with protein, fibre and other essential nutrients. Many breweries already sell or donate their spent grains to local farmers for use as animal feed. It can reduce waste and offer a possible source of revenue. The circular economy's principles of minimizing waste with reusing and recycling resources align with the use of by-products for the energy and feed recovery. Therefore, the cyclic approach has enormous potential for economic value addition with attainment of SDGs.

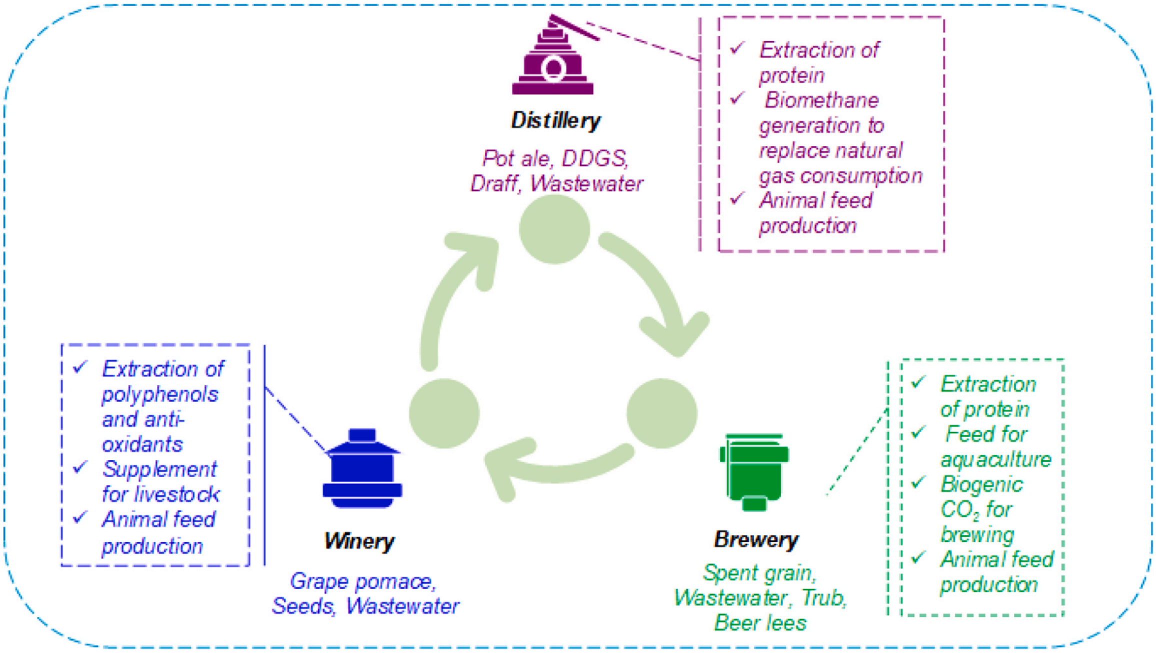

Fig. 4. Application of by-products from alcoholic beverage industry in a circular economy framework.

CRediT authorship contribution statement

Manish Kumar: Writing – original draft, Formal analysis, Data curation. **V. Vivekanand:** Writing – review & editing. **Aakash Chawade:** Writing – review & editing. **Rajni Kumari:** Writing – review & editing. **Kunwar Paritosh:** Writing – original draft, Formal analysis, Data curation, Conceptualization. **Nidhi Pareek:** Writing – review & editing, Supervision, Project administration.

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.

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Data availability

Data will be made available on request.

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