Journal of Cleaner Production 447 (2024) 141527

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Review

Lifting craft breweries sustainability through spent grain valorisation and renewable energy integration: A critical review in the circular economy framework

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ARTICLE INFO

Handling Editor: Zhen Leng

Keywords:
Brewery spent grain
Microbreweries
Anaerobic digestion
Life cycle assessment
Resource recovery
Solar energy

ABSTRACT

Due to the constantly growing customers' demand for local products, a significant rise in craft breweries' number, as well as in craft beer production, has been observed in the last years. The sustainability of craft breweries is a hot scientific topic, which involves water and waste management, energy efficiency, and renewable energy implementation. Life cycle assessment (LCA) and life cycle costing (LCC) are useful tools to compare alternative waste management pathways in a standardised manner, highlighting the hotspots with the highest environmental/economic impact.

Brewery-spent grain (BSG) represents the main organic by-product of beer production; traditionally, it has been used as animal feed. However, not always there are enough farms to utilise all the produced BSG locally, especially in developed countries and industrialised areas, so alternative solutions should be exploited. This review gives a thorough overview of the different technological pathways for BSG valorisation considering the state-of-the-art of research on the topic, including both traditional (animal feed, composting, anaerobic digestion) and innovative (thermochemical processes, pellets production, food production, chemicals' extraction) solutions. The applicability of each technology to craft breweries is specifically discussed. To enhance craft breweries' sustainability and decarbonise industrial processes, renewable energy generation is considered as well either through photovoltaic (PV) or solar thermal: while solar thermal implementation appears cumbersome due to the batch nature of the processes, PV installation is a mature, simple and straightforward solution. Geothermal energy integration is mentioned as well. Finally, a lack of studies on LCA/LCC application to compare the presented alternative BSG management pathways is highlighted, requiring intensive future research.

1. Introduction

A craft brewery, also known as a microbrewery, is a small-scale brewery primarily serving the local or regional market and producing beer in small quantities (Baiano, 2021). Craft breweries specialise in experimenting with unique recipes and ingredients, and can provide a large selection of specialised and artisanal beers (Baiano, 2021). There is currently no universal definition for a craft brewery (Table S1), and with the growing popularity of craft beer, a set definition would provide greater clarity. The European Union (EU) has endeavoured to create a standard definition but within individual member countries, there are different definitions. In Table S1, the specific criteria required to qualify a brewery as a craft brewery are summarised.

Some countries separate this industry into different segments: in the US, the Brewers Association has divided the craft brewery industry into six sections, including microbreweries, brewpubs, taproom breweries, regional breweries, contract brewing companies, and alternating proprietors (Brewers Association, 2019). There are even countries, such as Ireland, where multiple and contrasting definitions exist.

The brewing process forecast various steps (Fig. 1): the first stage, typically performed by grain suppliers, is malting, which involves soaking the grains and allowing them to germinate. The germinated grains are dried in a kiln to inhibit further growth and maintain enzymatic activity. The operations executed at the brewery normally start in a mash tun, where the crushed malted grains (i.e., malt) are combined with hot water to maximise enzyme activity and sugar extraction. After

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https://doi.org/10.1016/j.jclepro.2024.141527
Received 28 August 2023; Received in revised form 24 December 2023; Accepted 27 February 2024
Available online 28 February 2024

mashing, the brewery spent grains (BSG) are removed from the wort in lautering. Since most of the starches were transformed into sugars, the BSG's starch content has been reduced but it still contains fibre and valuable nutritional elements, including vitamins, fibres, and proteins. BSG is commonly made up of husks, protein, cellulose, and some leftover carbs, and has a multitude of uses in agricultural and food industries, such as utilisation as animal feed, bioenergy and fertiliser production, food or feed additive (Aroh, 2019).

The collected wort is then transferred to a brew kettle where it is brought to a boil; hops are added for bitterness, flavour, scent, and as a natural preservative. After boiling, the wort must be quickly chilled to a temperature conducive to yeast fermentation. The cooled wort is transferred to a fermentation vessel and mixed with yeast to start fermentation. The fermentable carbohydrates are consumed by the yeast, turning them into alcohol and carbon dioxide. After primary fermentation, the beer goes through conditioning. The final beer product is filtered once it has acquired the appropriate flavour and purity.

Craft beer popularity and the number of craft breweries have greatly increased in recent years. Europe and the US account for the majority of craft beer producers worldwide, with 46% and 43% of craft beer producers respectively (Baiano, 2021). Within the European market, there has been a steady growth in both the number of craft breweries and the market volume produced since 2008 (Conway, 2023; Zenith Global Ltd, 2017), despite the negative impacts caused by the COVID-19 pandemic (Fig. 2).

Overall, the UK, Italy, France, and Germany have the highest number of breweries in Europe (Baiano, 2021). The European craft beer market is anticipated to expand significantly between 2022 and 2027, with a Compound Annual Growth Rate of 8.62% (Mordor Intelligence, 2022). Additionally, the developing economies of Croatia, Romania, and Serbia are major drivers of the craft beer market, due to rising incomes that stimulate a wider consumption of craft brews (Mordor Intelligence, 2022).

The growth in the number of craft breweries in the US was not as greatly affected by COVID-19 as the EU Market (Conway, 2023). Craft beer represented 13.2% of the market share in 2022, and was distributed as follows: 65.4% came from regional breweries, 9.2% from taprooms, 7% from brewpubs, 17.5% from microbreweries, and 0.9% from contract brewing companies (Brewers Association, 2019).

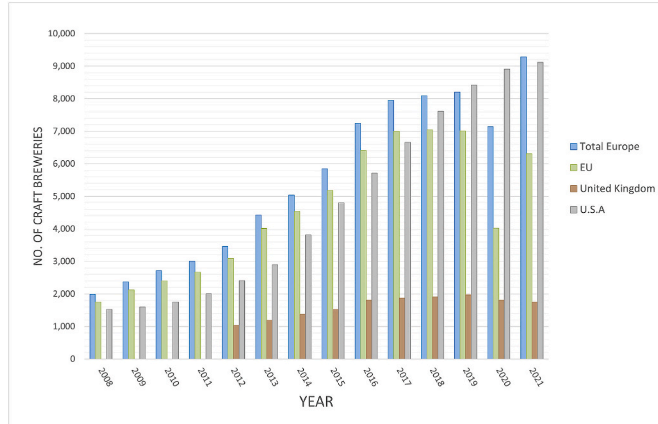

Fig. 2. Development of the craft beer industry (2008–2021).

Breweries are major water consumers (3–10 L of wastewater generated per L of produced beer) and generate significant environmental burdens. Most of the water (65%) leaves the brewery with wastewater, including the water used for bottle washing and pasteurisation, while a large water fraction (26%) is included in the produced beer, and the rest (9%) leaves the brewery in the produced by-products, but also through evaporation and process losses (van der Tuin, 2022). The most relevant environmental challenges connected to beer production (Fig. 1) include energy and water consumption, emissions to air, waste and by-product generation (Olajire, 2020). BSG, spent hops and surplus yeast are the main by-products of brewing operations (Kerby and Vriesekoop, 2017), while solid waste includes glass, paper, cardboard, plastic, wood, oils,

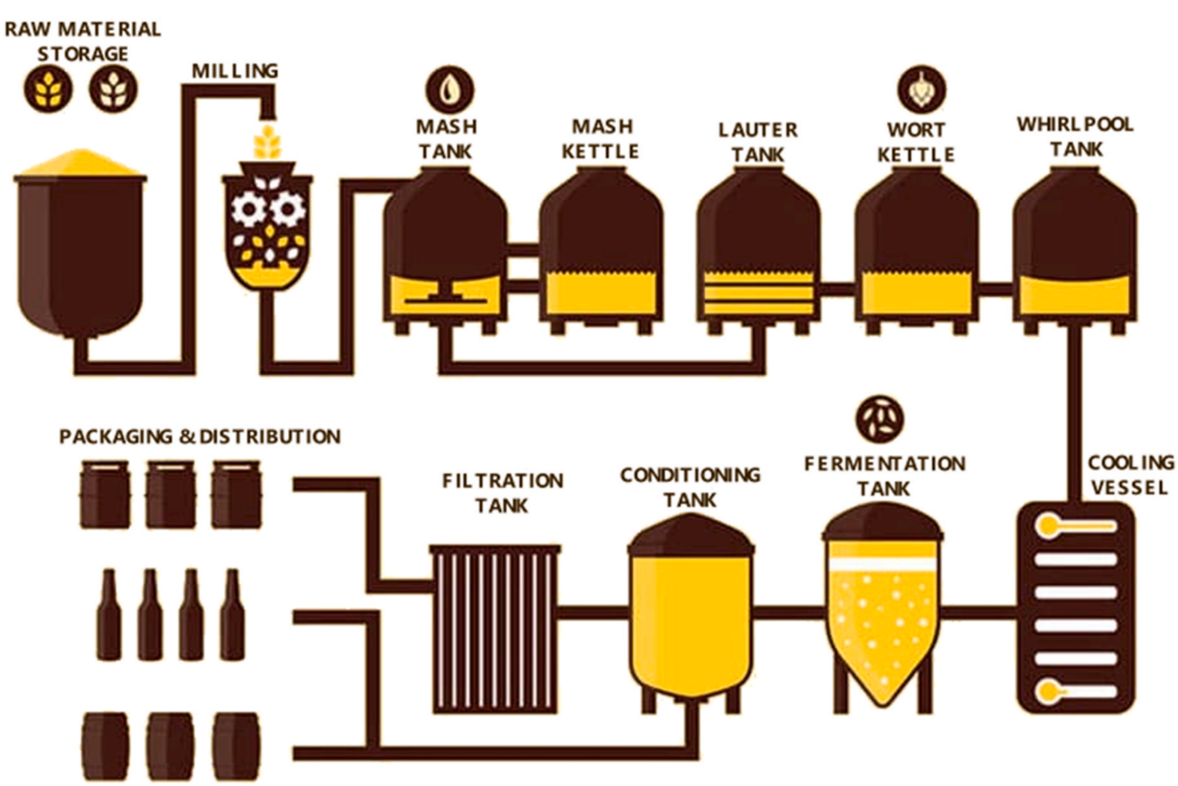

Fig. 1. Schematical representation of the beer production process.

and green residues (Olajire, 2020). BSG is undoubtedly the most relevant organic residue in breweries, with produced amounts around 14 kg/hL, so its proper valorisation and disposal appear crucial to raise the overall sustainability of craft breweries.

As regards energy, utilities costs amount to 3–8% of breweries' budget: breweries are relatively intense users of both thermal and electric energy, with craft breweries showing a generally lower energy efficiency (Cimini and Moresi, 2018; Salazar Tijerino et al., 2023). Thermal energy is used to produce steam in boilers, which is then applied to wort boiling and water heating, as well as in the bottling hall. Electricity, instead, is mainly needed for refrigeration purposes, bottling, wastewater treatment, and brewhouse operations (Olajire, 2020). Sustainable practices that can be implemented in craft breweries to limit their environmental impacts include water and energy use reduction, increased energy efficiency with renewable energy generation, the utilization of local and/or organic ingredients, and nurturing a culture that promotes sustainability (Hoalst-Pullen et al., 2014). However, organic products sometimes show lower product yields, increasing the environmental impact calculated per kg of product, while the impact is generally lower when calculated per area of farmed land (Meier et al., 2015), so standardised approaches must be used to assess overall process sustainability. In this framework, environmental assessment tools such as life cycle assessment (LCA) and life cycle costing (LCC) have raised in popularity to rank alternative management strategies or to point out the most impacting hotspots in the process chains (Salazar Tijerino et al., 2023). Recently, an improved environmental attitude and environmental proactivity has been highlighted in craft breweries, thanks to the implementation of strategies to reduce energy and resources consumption, limit waste generation and manage the process more consciously (Rahman et al., 2023; Sozen et al., 2021).

The rising interest in craft breweries is associated with the necessity to move towards circular economy principles. As BSG represents the main organic sub-product of beer production, its proper management and valorisation appear fundamental. A significant number of scientific papers and reports have been published in the last 10 years concerning craft breweries' sustainability (Cipollaro et al., 2021; Ness, 2018); however, an up-to-date review paper on this topic is missing. In this work, after presenting the applied methodology (Section 2), the environmental impact of craft breweries is examined (Section 3), with a focus on LCA and LCC. Sections 4 and 5 deal with BSG valorisation pathways, focusing both on well-established and innovative processes, and discussing their applicability to craft breweries. Section 6 deals with renewable energy implementation, through photovoltaic (PV) or solar thermal energy, but also through geothermal energy, to reduce fossil fuel consumption, decarbonising beer production processes. The future research needed to enhance the overall sustainability of craft breweries is depicted throughout the sections, considering the current state-of-the-art.

2. Methodology

The literature analysis was made by searching in Scopus and Google Scholar databases all the relevant studies related to craft breweries published in the last ten years (2013–2023). As for BSG management, the used keywords were "microbrewery" or "craft brewery" in combination with "spent grain" and "management" or "valorisation", while for renewable energy generation, the search was conducted through the keywords "microbrewery" or "craft brewery" and "renewable energy". Finally, the LCA/LCC studies were retrieved by searching the keywords "microbrewery" or "craft brewery" combined with "life cycle assessment" or "life cycle costing". In addition, older but fundamental studies, such as highly-cited review papers, were included in the assessment. Not only scientific papers but also reports and master's/Ph.D. thesis were considered whenever pertinent. Finally, additional case-studies not available in the literature, such as those connected to geothermal energy generation, were obtained from a dedicated search on the Internet.

3. Environmental impact and LCA/LCC application

LCA is a standardised tool to compare different management scenarios in terms of their environmental impacts and rank the alternative technological solutions (Mainardis et al., 2021b). LCA is often coupled with LCC to give an indication of the economic aspects, besides the environmental burdens (Martin et al., 2022).

The literature studies related to LCA application to craft breweries are summarised in Table S2: most of the studies aim to improve the overall sustainability of craft breweries, considering the generally higher environmental impact of small-scale breweries (Cimini and Moresi, 2018; Salazar Tijerino et al., 2023) as well as their raising popularity (Shin and Searcy, 2018). Packaging has a relevant impact on the overall production chain: steel cans show the lowest impact on the impact categories of primary energy demand, abiotic resources depletion, acidification, and marine and terrestrial toxicity, while bottled beer is the worst environmental option for primary energy demand and global warming (Amienyo and Azapagic, 2016). However, the environmental impact hotspots of craft breweries are significantly different than those of large breweries, especially when the beer is distributed in reusable casks and kegs (Morgan et al., 2021), thus local boundary conditions should be carefully evaluated. A similar behaviour has been highlighted regarding the economic profitability of the investment in innovative technologies, such as instantaneous water heating systems (as an alternative to steam boilers): despite showing a reduction in labour and gas costs, their profitability in terms of net present value and internal rate of return is limited by the small brewery scale (Salazar T. et al., 2021). Moreover, the discount rate plays a major role in determining the profitability of the investment.

Possible solutions to reduce the environmental impacts in craft breweries include replacing virgin materials for packaging with recycled ones, substituting road with rail transport, implementing PV energy (de Paula Diniz et al., 2021), substituting barley grown abroad with local one (Cimini and Moresi, 2018). The limited financial resources of craft breweries may sometimes impair the implementation of environmentally sustainable practices (Shin and Searcy, 2018), so dedicated incentive schemes are needed to fully move towards circularity. Also, data availability is often a challenge for craft breweries due to their limited technical knowledge (Shin and Searcy, 2018).

A remarkable research compared the environmental performances of conventional and innovative BSG stabilization strategies (dehydration, lacto-fermentation, freeze-drying, methanation, composting, animal feed utilization) for upcycling in human consumption (Petit et al., 2020), highlighting that the newly introduced processes may markedly contribute to the environmental impacts. However, the avoided environmental impacts connected to human consumption must be considered in the analysis as well (i.e., the upcycled material substitutes a quota of food from a "conventional" source).

From the conducted literature analysis, energy efficiency and waste management appear as fundamental aspects. However, intensive research is needed given that the total number of studies dealing with these aspects is relatively small. Thus, the following sections specifically focus on the possible BSG valorisation pathways (Sections 4 and 5), specifically discussing their applicability to craft breweries. Successively, given the relatively low energy efficiency of craft breweries, the possibility of improving their energy balance by implementing renewable energies is discussed (Section 6).

4. Brewery spent grain: characterization and traditional valorisation pathways

As previously introduced, BSG represents the main organic residue produced in breweries (about 85% of generated by-products) (Sperandio et al., 2017), and thus its management is a key aspect to enhance the overall sustainability of breweries. The most significant challenge to implementing any valorisation route is given by the high moisture and organic matter content of the material (70–80% w/w), which requires either prompt utilization (e.g., transportation to local farms and utilization as animal feed) or intensive drying to make it stable and prevent mass losses during storage. Storage is fundamental considering the high moisture content and the significant polysaccharide and protein concentrations of BSG, which lead to fast deterioration and spoilage, with possible health hazards and odour issues (Capasso and Arne Martin Fevolden, 2019). Most craft breweries currently lack technologies (e.g., pressing/drying equipment, cold storage) for long-term BSG preservation (Capasso and Arne Martin Fevolden, 2019), so utilisation as animal feed still appears as the preferred route, if enough farms are present in the local geographic area to utilise all the generated BSG, avoiding long transportation distances.

Relevant BSG characteristics which impact the possible end-uses are summarised in Table 1. Some general features can be underlined: a total solids (TS) content in the range of 16–27% w/w, a high volatile solids (VS) content (VS/TS ratio above 95%), a limited ash percentage (typically below 5%), a high carbon (C) and nitrogen (N) content (respectively 45–50% and 2.4–4.4%) and a good higher heating value (>17 MJ/kg). A remarkable study focused on craft breweries in the USA reported 38.2% fibre, 33.1% starch, 18.7% protein and 6.3% lipid content in BSG, while fermentable sugars (maltose, maltotriose, glucose and fructose) were detected at 8.2% (dry basis) (Jin et al., 2022). The measured concentrations of lignin, cellulose, and hemicellulose in BSG are respectively in the range of 9.19–56.74%, 0.3–40.20%, and 19.27–41.9% (Jackowski et al., 2020). As concerns macromolecules, a Brazilian case study reported carbohydrates, total proteins, total fats, and crude fibres to be respectively 1.89 % w/w, 4.89 % w/w, 2.67 % w/w, and 4.19 % w/w (Onofre et al., 2017). These physicochemical BSG characteristics suggest a general amenability to apply biological processes, despite the high lignin concentration potentially limiting the full conversion of the organic substances embedded in BSG. BSG stabilization is mandatory when long-term storage or preservation is required due to its high moisture and organic matter content, which stimulates a fast deterioration. The observed fluctuations in BSG characteristics, especially from craft breweries, depend on several factors, such as area of production, harvest time, barley variety, malting and mashing conditions, quality, and type of additives used during the brewing process (Assandri et al., 2021b).

The possible pathways for BSG valorisation are graphically summarised in Fig. 3, including both conventional and innovative processes. The processes conventionally applied to dispose of BSG include reuse as animal feed and soil application (Section 4.1), fertiliser recovery through composting (Section 4.2), and energy recovery through anaerobic digestion (AD) (Section 4.3).

4.1. *Animal feed and soil application*

Traditionally, BSG has been used as animal feed, especially for cattle farms (Brekke et al., 2019), as it contains high concentrations of proteins and fibres (McCarthy et al., 2013). BSG is an excellent feed for ruminants, providing all the essential amino acids when combined with low-cost N sources such as urea (McCarthy et al., 2013), and is cheaper than soybean (Assandri et al., 2021b). BSG utilization as animal feed can reduce the environmental impact of cattle breeding in comparison to solvent-extracted soybean meal (SBME) usage by providing a nutritional co-product, especially when spent grain is locally produced (Hörtenhuber et al., 2011; Saget et al., 2022). Despite being a good practice for the bioeconomy, placing it between "recycle" and "reuse" in the waste pyramid, the fast deterioration of BSG, due to its high content of moisture, proteins, and fermentable sugars (Assandri et al., 2021b), requires the local presence of farmers and efficient transport infrastructure (Brekke et al., 2019). Furthermore, currently, in developed countries most farmers opt for intensive centralised farming (Brekke et al., 2019; Mainardis et al., 2019), instead of traditional decentralised farming which is still the most common solution in developing countries (Aliyu and Bala, 2011). In the absence of local farms, huge transport costs are incurred by craft breweries to dispose of the produced BSG (Mainardis et al., 2019). However, specific local conditions should be considered case by case, as the availability (or unavailability) of farms and the applied farming strategies differ substantially in each geographical area.

As BSG is typically given away for free to farmers, no additional economic income is generated. As a result, high interest is currently being given to alternative valorisation pathways, which include both mature technologies (composting, AD) and emerging solutions (food production, energy recovery, pyrolysis) (Brekke et al., 2019), despite their full-scale application is still limited.

Besides utilization as animal feed, direct BSG soil application has been reported in the literature, especially in Africa (e.g., Nigeria) (Jackowski et al., 2020; Ojeniyi et al., 2007): higher fruit yields were observed after soil application of 12.5 t/ha of BSG, showing comparable effects to conventional NPK fertilisers at a dosage of 200 kg/ha (Ojeniyi et al., 2007). An Italian study compared the effects of raw and bioprocessed (enzymatic treatment coupled with fermentation) BSG as an organic soil amendment for escarole cultivation, increasing soil organic and total nitrogen content (respectively, +72% and +42%), and doubling phosphorus availability (Cacace et al., 2022). Although there was no difference in the number of leaves between raw and bioprocessed BSG trials, the average fresh weight per escarole head was higher in pots amended with bioprocessed BSG. However, care must be posed in direct soil application of untreated BSG, as it is rich in VS, moisture (Table 1), and microorganisms, which may alter the natural soil equilibrium, leading to long-term negative effects.

Table 1
Physicochemical characteristics of brewery spent grain (BSG) from craft breweries (n.a.: not available).

Parameter	Sperandio et al. (2017)	(Mainardis et al., 2019), brewery 1	(Mainardis et al., 2019), brewery 2	Dudek et al. (2019)	Świechowski et al. (2023)	Coronado et al. (2020)	Vitanza et al. (2016)
Moisture (% w/w)	72.9	84.0	76.7	78.7	79.6	72.3	81.3
Ash (% w/w)	5.3	0.46	4.9	3.1	3.1	4.1	2.5
Total Solids (TS) (% w/w)	27.1	16.0	23.0	21.3	20.4	27.7	18.7
Volatile Solids (VS) (% w/w)	25.7	15.53	18.1	20.6	19.6	21.7	18.2
VS/TS (%)	94.7	97.15	78.6	96.9	96.2	78.5	97.5
C (% of TS)	45.7	47.5	45.6	50.5	48.6	43.6	n.a.
H (% of TS)	9.0	6.5	6.7	7.2	7.0	6.2	n.a.
N (% of TS)	4.2	2.9	2.4	3.6	4.4	3.5	n.a.
Gross calorific value (MJ/kg)	16.9	n.a.	n.a.	20.0	20.8	18.7	n.a.
Net calorific value (MJ/kg)	13.7	n.a.	n.a.	17.74	n.a.	n.a.	n.a.

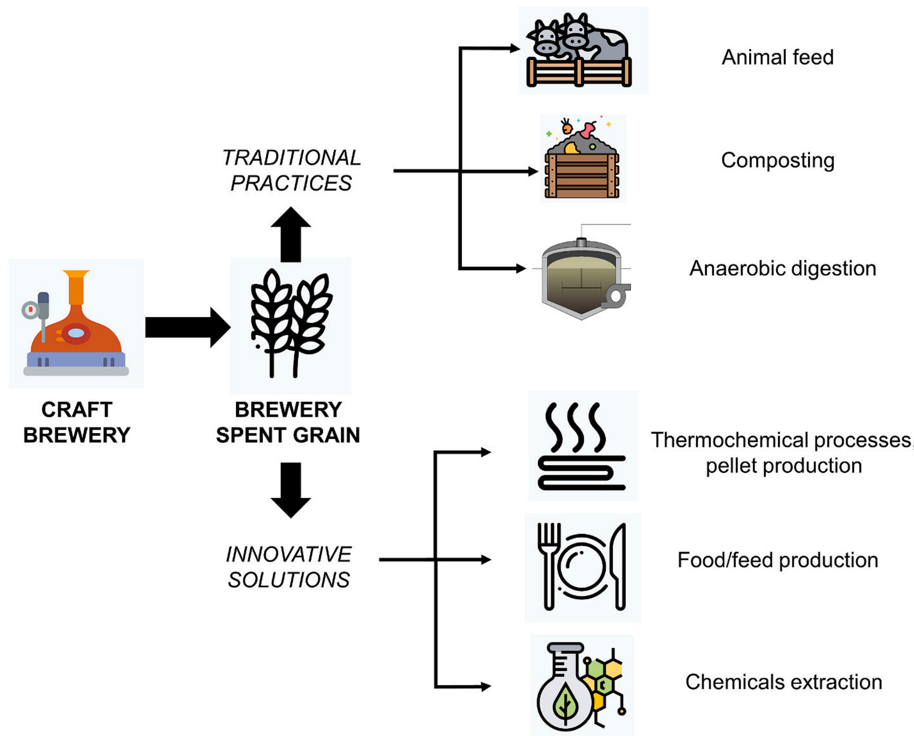

Fig. 3. Traditional and innovative valorisation pathways for BSG.

4.2. Composting

BSG can be directly applied to the soil to increase the amount of organic matter, stabilise the aggregates, stimulate nutrient mineralization, and favour water retention (Aboukila et al., 2018); however, considering that raw BSG is microbiologically unstable, a stabilization process, such as composting or vermicomposting, is strongly suggested (Bianco et al., 2022).

Composting is one of the simplest technologies for organic waste stabilization and is a self-heating biological conversion process, as the exothermal decomposition reactions generate the heat required to stabilise and sanitise the organic waste (Sarkar et al., 2016).

The physicochemical characteristics of BSG, especially the high moisture content and the low carbon-to-nitrogen (C/N) ratio, make it unsuitable for direct composting (Assandri et al., 2021b), so process modifications are required. Adding lignocellulosic bulking agents, such as wheat straw, reduces the moisture level while adding carbon-rich by-products promotes a proper composting process by adjusting the C/N ratio to the optimal values of 20–30 (Assandri et al., 2021b). Livestock manure can be cast into the co-composting mixtures to provide specialised bacteria for the composting process, which may be absent in the original BSG (Assandri et al., 2021a). It was recently demonstrated that it is possible to perform composting of BSG alone in about 50 days, leading to a high-quality compost (neutral pH, C/N ratio of 13.7, high concentrations of P and K, and negligible concentration of heavy metals); however, the preventive addition of carbon-rich materials was again suggested to enhance the C/N ratio for smoother operations (Magnoudéwa et al., 2022).

Compared to traditional composting processes, vermicomposting exploits microorganisms and earthworms to fragment, bio-oxidise and stabilise organic wastes (Lazcano et al., 2008). Differently from conventional composting, vermicomposting is conducted at milder temperatures (25–40 °C) and higher moisture levels (70–90%) (Tognetti et al., 2005). Earthworms can easily adapt to a broad range of environmental conditions (pH, initial moisture content, and C/N ratio); however, specific pre-treatment may be required to increase substrate biodegradability for earthworms (Bianco et al., 2022). In the case of BSG, drying at 45 °C for 48 h (Saba et al., 2019), inoculation with microorganisms (Wei et al., 2019) and fungi (Kucharska et al., 2018) were studied before vermicomposting, highlighting promising results in terms of compost maturity and respect of legal requirements.

4.3. Anaerobic digestion

AD is a mature stabilization technology for a pool of organic substrates, including sewage sludge, agro-industrial residues, animal manure, and the organic fraction of municipal solid waste. AD is operated either in mesophilic (35–45 °C) or thermophilic (55–60 °C) conditions (Labatut et al., 2014) through conventional or high-rate reactors (Mainardis et al., 2020), leading to the generation of valuable biogas, together with digestate. If it complies with the local legislation standards, which typically require a minimum nutrient concentration and establish maximum heavy metals and pathogen thresholds, the digestate can be applied to agricultural soils (Khakbaz et al., 2020).

The concept of enhanced AD has recently raised interest, meaning the application of pre-treatment techniques or the dosage of additives (biochar, granular activated carbon, macro or micronutrients), to enhance the digestibility and the subsequent methane production from poorly degradable substrates, such as sewage sludge (Mainardis et al., 2021a) or lignocellulosic biomasses (Kang et al., 2022).

Similar to what was previously observed for composting, the mono-digestion of BSG is technically feasible, but often leads to process inhibition due to the unbalance in nutrient concentration (C/N ratio) and the generation of toxic by-products, such as p-cresol (i.e., a phenolic intermediate) (Bougrier et al., 2018). The most relevant literature studies related to the enhanced AD of BSG are summarised in Table S3. Nearly all the studies were performed in mesophilic conditions, apart from the study reported in (Malakhova et al., 2015), where mesophilic and thermophilic conditions were compared, highlighting the superior results of the former.

Thermal pre-treatment (autoclave) disrupts the lignocellulosic structures and is efficient in solubilising carbohydrates in BSG, leading to a significant increase in methane yields (from 171.6 up to 290.1 mL CH_4/g total volatile solids- TVS) (Gomes et al., 2021). However, the additional methane yield should be sufficient to sustain the heat needed for the thermal pre-treatment to make full-scale application sustainable (Mainardis et al., 2021a). Microwave-assisted alkali pre-treatment (Kan et al., 2018) and ultrasonication (Buller et al., 2022) showed good results on BSG as well, with methane yields respectively up to +52% and +401% (the latter one, however, starting from very low values of 26.72 L CH_4/kg TVS); nonetheless, electricity demand and chemical consumption often limit their full-scale applicability. Ultrasonication is known to require substantial electricity levels, especially at the laboratory-scale (Mainardis et al., 2021a). Multi-objective optimization of laboratory-scale biochemical methane potential tests is required to get the best energy output, achieving a satisfying balance between organic matter solubilization, additional methane yield and energy/costs required to pre-treat the material (Kan et al., 2018). Specific tests at the laboratory or pilot scale should be conducted case-by-case to establish the optimal pre-treatment conditions.

Two-stage AD is an excellent solution for a stable anaerobic process of BSG: a solid-state reactor for hydrolysis and acidogenesis was proposed as a first step, followed by a granular reactor for methanogenesis, showing high TS removal and good methane yields (224 L CH_4/kg TS_{added}) (Panjičko et al., 2017).

Another possibility to enhance methane production from BSG is the co-digestion process, which couples locally available organic substrates having synergic characteristics in terms of C/N ratio, VS content, macro, and micro-nutrients, such as sewage sludge, agricultural residues and cheese whey (Malakhova et al., 2015; Miller et al., 2021; Mudzanani et al., 2021; Oliveira et al., 2018; Szaja et al., 2020; Szaja and Montusiewicz, 2019). The exploitation of locally available co-substrates in AD can be not only economically convenient but also technically useful to stabilise the process and enhance energy yields, addressing BSG shortcomings (Miller et al., 2021). Besides BSG, spent yeast represents another sub-product of the beer production process, with an excellent CH_4 production potential (up to 487 NL CH_4/kg VS_{added}) due to its substantial biodegradability (Mainardis et al., 2019; Oliveira et al., 2018), thus, co-digestion of BSG and spent yeast is recommended in all cases. Co-digestion of brewery residues, such as BSG and spent yeast, can provide up to 80% of the required thermal energy needed for the process (Oliveira et al., 2018).

The supplementation of trace elements to the AD reactor was recently proposed by comparing for each nutrient the measured concentration in BSG and the optimum concentration (Bougrier et al., 2018); higher methane yields (220–350 NL/kg VS) and a more stable pH were obtained in the reactors supplemented with trace elements. However, punctual BSG quality monitoring and nutrient dosage are required, which may be cumbersome for craft breweries.

As concerns biochar (BC) and granular activated carbon (GAC) supplementation, which has recently become popular in the AD field, while moderate dosages can improve syntrophic electron transfer and alleviate biomass inhibition by volatile fatty acids (VFA) or unionised ammonia, excessive amounts of these additives usually show inhibitory effects (Dudek et al., 2019; Świechowski et al., 2023). Considering that the results given by GAC/BC addition strongly depend on the specific BSG characteristics (Mainardis et al., 2019; Świechowski et al., 2023), it is recommended to avoid dosing these additives when the process is not prone to inhibition. The specific dosage to be applied should be in any case selected through laboratory or pilot-scale studies, given the significant differences obtained in the literature.

The interconnection between pyrolysis and AD (e.g., BC production from digestate pyrolysis and successive BC utilization to amend the AD process) is another topic of current scientific interest (Catenacci et al., 2022) and could be potentially applied to BSG.

Another interesting approach to improve the AD process of BSG is the inoculation of active hydrolytic bacteria (bio-augmentation), which accelerates the rate-limiting step (hydrolysis), increasing methane yields (+4.9–17.8%) (Čater et al., 2015). Limited studies have been conducted, however, this approach appears potentially applicable also to craft breweries.

More generally, the key point to improve process conditions in AD of BSG appears to be the digestibility enhancement, due to its lignocellulosic nature (Mankar et al., 2021) which can be achieved either by substrate pre-treatment, proper selection of co-digestion substrates, or hydrolytic bacteria inoculation.

As regards the energy and economic aspects of AD, the biorefinery concept application to breweries could lead to significant profits, due to the exploitation of biogas for electricity and heat production (or eventually biomethane generation) as well as digestate sale for agriculture (Sganzerla et al., 2021). However, the results strongly depend on brewery size, with large breweries showing pay-back times even below 4 yr and craft breweries highlighting much longer pay-back times (14–19 yr) (Sganzerla et al., 2021). Thus, the most complex technological solutions (such as biogas upgrading) appear not to be currently applicable to craft breweries due to economies of scale.

5. Innovative solutions

Alternative solutions for BSG valorisation (Fig. 3) include thermochemical processes (Section 5.1), pellet production (Section 5.2), utilisation as a food ingredient (Section 5.3), extraction of valuable compounds (Section 5.4), and other uses (Section 5.5). The technologies presented in Sections 4 and 5 are then critically compared in Section 5.6.

5.1. Thermochemical processes

Pyrolysis, hydrothermal carbonization/liquefaction (respectively HTC and HTL), gasification, and torrefaction, have recently attained interest in literature as an alternative treatment to conventional composting or AD. A general feature of thermochemical processes is the production of a pool of different products (a solid fraction, called char, biochar, or hydrochar, a liquid stream, and a gaseous flow) (Catenacci et al., 2022). Process conditions (temperature, heating rate, etc.) can be tailored to enhance the yield of the desired fraction: higher temperatures increase the production of gaseous products due to enhanced degradation of macromolecules (Catenacci et al., 2022).

Most interest is currently being devoted to chars and to the liquid (bio-oil) fraction, given the flexibility of possible applications; biochar/hydrochar, in fact, can be used as a soil amender, as an adsorbent, but also in energy recovery applications, due to its high calorific value (Kambo and Dutta, 2015). Bio-oil, instead, is a condensed dark brown liquid, also called pyrolysis oil, pyrolytic tar and wood oil, which consists of a mixture of oxygenated compounds such as acids, aldehydes, ketones, phenols, aromatics, esters, ethers, alcohols and carbohydrates (Lachos-Perez et al., 2023). Bio-oil can be upgraded to extract high-value chemical compounds, such as furfurals, organic acids and levoglucosan, which are essential precursors of diesel fuels, bio-binders, bio-based carbon materials and polyurethane foams (Lachos-Perez et al., 2023). Generally, slower heating rates and lower temperatures improve the yield of the solid and liquid fractions (Catenacci et al., 2022).

Thermochemical conversion studies related to BSG valorisation are summarised in Table S4. Pyrolysis and HTC are the main investigated processes; however, most studies are performed at laboratory or pilot-scale conditions, due to the still uncertain energy/economic balance of full-scale applications. As concerns char application, three main solutions are exploited, namely: (i) use as a fuel (due to good higher heating value, limited ash and sulphur content) (Borel et al., 2020; Jackowski et al., 2019); (ii) application as an adsorbent, thanks to its high surface area (Sieradzka et al., 2022), with interesting adsorption capacities at moderate pyrolysis temperatures (400 °C) (Xi et al., 2014); (iii) soil application, due to the high C and N content (respectively 10–12% and 13–20% of the original values) and C sequestration capability (Balogun et al., 2017; Sanna et al., 2011).

HTC processes are particularly useful for the treatment of wet biomasses such as BSG; lignocellulosic substrates, in addition, are excellent precursors for C-rich materials with applications in energy storage, as catalysts, environmental additives, and biofuels (Khan et al., 2019). In HTC, a compromise must be found between improved char properties and reduced solid yield observed at higher temperatures (Lorente et al., 2020), while in pyrolysis a moderate process severity is often beneficial both for char yield and properties. Interestingly, HTC and pyrolysis can be coupled in series to further improve both char yield and properties (Olszewski et al., 2020).

Regarding bio-oil, it was shown that BSG-derived bio-oil is rich in phenols, ketones (chemical precursors), and pyrazines, which can be utilised in the pharmaceutical industry (Borel et al., 2020). In addition, the presence of saturated fatty acids (palmitic, linoleic, oleic acids) suggests bio-oil utilisation for bio-diesel production (Balogun et al., 2017).

Finally, an interesting approach has been proposed by Parchami et al. (2021): BSG was pre-treated through a hydrothermal process to solubilise starch and proteins, which were successively used to produce edible fungi. Pure fungal biomass, with a protein content of up to 59%, was obtained, showing an added commercial value.

5.2. Production of pellets

Despite showing a high carbon content (45–49% on a dry basis), the direct utilization of BSG as a fuel is limited by its excessive moisture (Table 1). An intensive drying step, which requires long residence times (about 100 min) is required prior to BSG combustion, reducing the moisture content to about 15% (Jackowski et al., 2020). Specific energy consumption required for BSG drying through superheated steam is in the range of 0.65–1.45 MJ/kg (Stroem et al., 2009).

An interesting alternative to direct combustion is the conversion of dried BSG into pellets that can be efficiently used for heat generation. According to the initial moisture content of the dried BSG (15–25%), a single passage (or multiple passages) in the pellet maker may be required; a binder (starch at 3% w/w) can be added as well (Sperandio et al., 2017). Another remarkable study investigated BSG pelletisation: the preliminary drying phase reduced moisture content from 70.5% to 12.5%, and the final pellet had a moisture level of 9.6% (Arranz et al., 2021). Considering the technical characteristics of the pellets required by UNE-EN ISO 17225-6, the only critical points were linked to durability, which can be enhanced by adding woody residues or increasing the extrusion rate, and the high N content, which leads to NO_x emissions (Arranz et al., 2021).

5.3. Food ingredient

BSG includes several elements (vitamins, fibre, minerals) which are useful to the human diet; however, due to its high moisture content, it must be processed (dried or frozen) directly after beer processing to avoid microorganisms' proliferation (Jackowski et al., 2020). The enrichment of durum flour with BSG augments fibres (+135%), β-glucan (+85%), and total antioxidant capacity (+19%) when compared to all-wheat durum flour (Nocente et al., 2019). The addition of 10% BSG allows getting the optimal organoleptic and technological characteristics of pasta (Nocente et al., 2019). Besides improving fibre content, adding BSG increases water absorption by bread, positively affecting its texture and volume (Steinmacher et al., 2012).

Similarly to bread, the addition of BSG flour to cookies affects their quality, even if negative outcomes can be observed regarding their appearance, smell, taste, chewiness, and hardness (Petrović et al., 2017). BSG flour addition in the proportion of 1:4 to wheat flour decreases the glycaemic index of cookies (Kirjoranta et al., 2016). The overall product cost of products added with BSG can be reduced as well.

Furthermore, BSG has been proposed as an additive to meat production (e.g., frankfurters), leading to increased fibre and lower fat content (Özvural et al., 2009). Similarly, the addition of BSG to snacks raises their fibre and protein content but increases their hardness, worsening their taste (Jackowski et al., 2020), especially when BSG content rises above 30% (Stojceska et al., 2008).

The negative effects of BSG addition, mostly linked to a worsening in sensory properties (colour and texture) (Naibaho and Korzeniowska, 2021), can be mitigated by adding corn starch and whey protein isolate (Kirjoranta et al., 2016). Another possible solution to reduce the unwanted effects given by BSG addition includes autoclave pre-treatment, which causes depolymerization in the BSG structure, enhancing its brightness and shelf-life, allowing to raise BSG percentage in commercial products (Naibaho et al., 2021). The consumer acceptability threshold of BSG content in food products comparable to commercial ones is 20%, even if 10–15% is considered optimal for sensory properties (Chetrariu and Dabija, 2023).

5.4. Extraction of valuable compounds

Many extraction processes have been proposed in the literature to get added-value substances from BSG, including arabinoxylans, polyphenols, antioxidants, glucose, and proteins (Jackowski et al., 2020). Phenolic compounds recently attained interest due to their antioxidant, anticarcinogenic, antiatherogenic, and anti-inflammatory properties, with beneficial effects on human health (Ikram et al., 2017; Karlović et al., 2020). Phenolic acids found in BSG include hydroxycinnamic acids (ferulic, p-coumaric, and caffeic acids), with concentrations of 6.5–336.3 mg/100 g dry matter (Ikram et al., 2017).

Furthermore, xylitol sweetener and lactic acid can be obtained, the latter showing wide applications in the chemical, food, pharmaceutical, textile, and leather industries (Karlović et al., 2020). Another valuable compound that can be isolated from BSG is pullulan, which is used in the pharmaceutical, food, and electrical industries, thanks to its ability to form fibres/films insoluble in oils (Karlović et al., 2020).

The extraction processes include enzymatic or alkaline hydrolysis, microwave-assisted or ultrasound-assisted extraction, solvent extraction, and supercritical carbon dioxide extraction (Jackowski et al., 2020; Karlović et al., 2020). The specific extraction method to be applied depends on the target compound and the extraction conditions, also considering economic and environmental aspects (Bonifácio-Lopes et al., 2020).

Recently, the pulsed electric field has been proposed as pre-treatment to improve phenolic compounds extraction from BSG: under optimal pre-treatment conditions in terms of electric field strength (2.5 kV/cm), frequency (50 Hz), and treatment time (14.5 s), it was possible to increase total free and bound phenolic compounds by 2.7 and 1.7 times (Martín-García et al., 2020). Consistently, in another study pulsed electric field at 2.8 kV/cm with 3000 pulses of 20 μs width allowed to significantly raise carbohydrate, protein, starch and reducing sugar yield in extracts from dark BSG (Kumari et al., 2019).

5.5. Other uses

As a lignocellulosic material, BSG is rich in hemicellulose and cellulose, which can be converted to bio-ethanol; for glucose extraction, material pre-treatment (acid, ultrasonic, microwave, or enzymatic hydrolysis) is again required (Mussatto, 2014). Interestingly, BSG cellulose and hemicellulose structures can be converted to ethanol without adding nutrients, as needed for other common ethanol-production biomasses (e.g., sugarcane bagasse) (Mussatto, 2014).

Furthermore, BSG seems to be a promising filler and reinforcing material, reducing the costs of bio-composites (Jackowski et al., 2020). BSG introduction into rubber allows for improving the acoustic features and the physical-mechanical absorption of the product (Zedler et al., 2020). Furthermore, polyurethane foam may be reinforced through BSG addition (Formela et al., 2017).

BSG can also be used in the construction sector: the addition of 5%

BSG to ceramic bricks is the best compromise between high mechanical bending strength and low thermal conductivity (Ferraz et al., 2013). BSG could also be an excellent substitute for sawdust in the brick industry, highlighting higher strength, reduced density after firing, and increased porosity (Russ et al., 2005).

Another field of application is the production of biodegradable packages: trays made out of BSG and starch showed comparable technical characteristics to expanded polystyrene trays (Ferreira et al., 2019).

In a circular economy framework, BSG can be reused as a carrier to immobilise yeast during fermentation in beer production processes, replacing commercial carriers, thanks to its ability to bind yeast, the absence of negative effects, the easy regeneration (through alkali solutions) (Karlović et al., 2020).

Finally, BSG is a promising material for paper-based products, such as towels, business cards, and coasters (Mussatto et al., 2006), but also for application as an adsorbent in gaseous or liquid streams (Mussatto, 2014).

5.6. Applicability to craft breweries

The advantages and downsides of each of the presented technological solutions for BSG valorisation are summarised in Fig. 4. A focus is made on the applicability of each technology to craft breweries, according to their specific features (limited plant size, rural/decentralised areas, importance of establishing local circular economies).

A British case study highlighted that urban craft breweries normally adopt a wider range of disposal/valorisation methods than rural craft breweries, the latter ones having a direct relationship with farmers (Kerby and Vriesekoop, 2017). Moreover, in craft breweries, spent yeast and hops are often mixed with BSG and treated together (e.g., through AD), as previously highlighted in Section 4.3.

Energy-intensive processes, such as thermochemical conversion and pellet production, are not currently applicable to craft breweries, as the energy balance may turn negative; however, the implementation of renewable energy generation through solar panels (Section 6) may enhance their applicability.

In order to compare and select alternative management scenarios, local conditions should be analysed, as a significant variability is encountered in BSG characteristics and brewery operations; in this sense, as previously introduced, LCA and LCC can be used to compare in a standardised way the environmental impacts and the economic burdens given by the different valorisation strategies presented in Sections 4 and 5.

6. Renewable energy integration in craft breweries

Renewable energy implementation offers several opportunities for industries to cut emissions, decrease operating costs and reduce their environmental impact. The adoption of solar energy as PV electricity generation and solar-thermal systems can help to reduce the reliance on fossil fuels both for electricity to drive the machinery and for heat to run the industrial processes. The food and beverage industry is one of the key sectors for solar energy integration since several processes (cleaning, drying, pasteurization, sterilization, or boiling) require a low-temperature level but a high overall energy consumption (Brunner et al., 2008). Breweries, in particular, show both a large heat demand at low-temperature levels and a large potential for heat recovery and energy efficiency improvement (Muster-Slawitsch et al., 2011). In addition to solar energy, geothermal energy can also be integrated into the brewing process.

Unsurprisingly, there is a growing interest in sustainability in beer

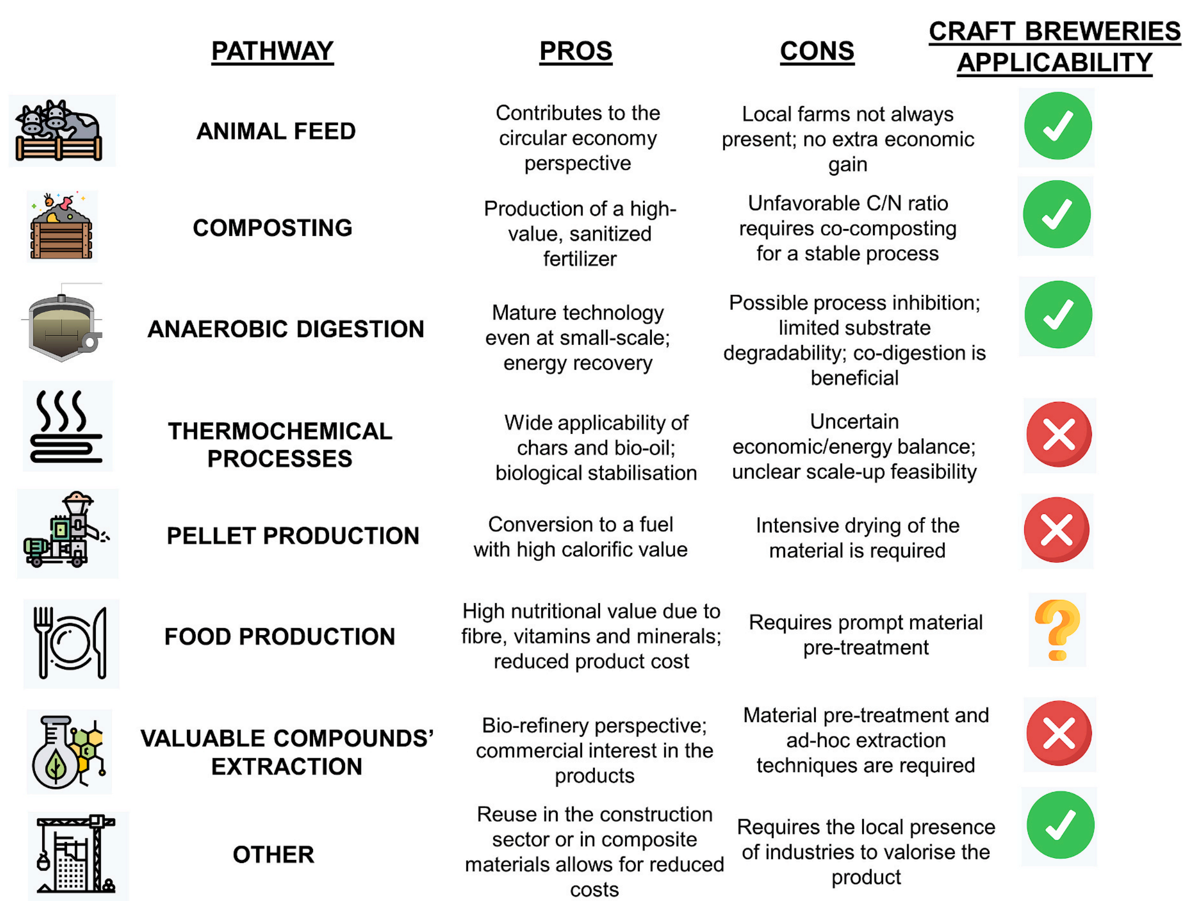

Fig. 4. Comparison of the main strategies for BSG valorisation and applicability to craft breweries.

production through the integration of technologies for energy conservation, renewable energy production, and BSG management. By analysing the factors that influence the adoption of eco-innovation (including technologies, practices, and products) in the Dutch brewing industry, it was highlighted that ethical responsibility, stakeholders, and opportunities/competitors play an important role, especially in small firms (Chappin et al., 2020). Among the 40 eco-innovations deployed between 2005 and 2017, 28 were related to heating/cooling and 8 were fuel/energy-related items. Affordability and pay-back time are the most important barriers to the deployment of eco-innovations in brewing industries, especially for small-scale breweries. In this context, renewable energy integration not only helps the sustainable development of the sector but can also help craft breweries to manufacture more profitable products and provide additional marketing and branding opportunities (Chappin et al., 2020).

6.1. Solar power systems

PV integration is quite straightforward and does not necessitate a strong process understanding (Crespo et al., 2019), making its application practical. On the other hand, solar thermal energy integration requires an in-depth knowledge of the process and identification of the best integration points with a thorough techno-economic perspective. This aspect justifies the limited integration of solar heat in breweries compared to PV installations (Pino et al., 2023). Although the data is outdated, 100 breweries were employing PV systems in 2019 globally (van der Linden and Wolf, 2019). This is anticipated to increase as breweries operating on PV have become popular in the US, Canada, EU, and Africa. US Brewers Association published an energy sustainability manual that compiled several case studies on the successful implementation of renewable energy projects in small breweries (Chastain et al., 2014), documenting the benefits of PV integration, such as supplying a reasonable fraction of total electricity demand and easiness in design and implementation.

The power demand profiles of micro and small breweries can significantly differ from one another; generally, they are often characterised by short-term peaks. Besides, they often lack a central monitoring and control system. Regarding energy consumption, three main characteristics of small to medium breweries make them less advantageous than their large counterparts (Pino et al., 2021): i) lack of funding to procure centralised efficient boilers and chillers running continuously; ii) the application of heat recovery technologies necessitates energy storage with additional costs due to batch operations; iii) they often lack the negotiation power to get reduced energy prices.

Moreover, the total installed capacity of PV in breweries is constrained by roof footprint, as well as by the limit of the electricity distribution company on renewable energy, and the investment payback time. PV can supply the heat/cold demand and mechanical power, therefore it is simpler and more advantageous compared to solar thermal systems in craft breweries, especially for the ones operating fully on electricity.

In a Chilean brewery expanding to a capacity of about 2700 hL/month, the integration of both solar thermal and PV technologies was assessed (Crespo et al., 2019): solar heat systems could supply 79% of the hot water demand with a payback period of 7 yr. Additionally, PV systems could cover 38.5% of the electric demand with a return on investment of approximately 4 yr. In a similar study, a techno-economic assessment of solar energy integration was conducted to provide 50% of electricity demand by PV and 30% of heat by a solar thermal system in a craft brewery in Seville, Spain (Pino et al., 2019). The net present value of the PV system was positive in all cases even when the excess energy was sold to the grid at 50% of the purchase price. However, the solar thermal system was only financially viable with direct incentives, mainly due to the low natural gas price in 2019. The integration of PV and solar thermal technologies resulted in a 51% electricity, 31% heat, and 3.8 ton-CO_2 reduction in a craft brewery with an annual capacity of 1200 hL (Pino et al., 2019); the need to conduct feasibility studies at local conditions was signalled before making investment plans, also considering the volatility of natural gas prices.

More recently, the potential of PV in breweries across Spain was estimated (Pino et al., 2021): PV integration could decrease the Levelised Cost of Heating and Cooling (LCOHC) by 6–11% in all regions, but the Discounted Payback Time (DPT) was between 9.8 and 19.5 yr, which is pretty long. Later, a more detailed analysis was performed for the economic feasibility of PV in a full-electric brewery in 52 capitals of Spanish provinces, accounting for different climatic conditions (Pino et al., 2023). LCOHC ranged between 0.285 and 0.332 €/kWh, showing a reduction of 19.4–39.9% with PV integration. The DPT was between 4.3 and 6.6 yr, which might be suitable. It can be deduced that the economic feasibility is very much dependent on the energy costs and there is a need for subsidies for clean energy integration to amortise the investment in the short term (Pino et al., 2021, 2023).

6.2. Solar thermal systems

There is great potential for solar heat application in breweries since all processes except wort boiling run below 100 °C and solar collectors can easily supply the required heat (Muster-Slawitsch et al., 2011). Generally, improving the energy efficiency of a brewery by implementing energy conservation measures is advisable before considering solar heat integration (Lauterbach et al., 2009), identifying the best integration point, boosting the benefit gained from solar-thermal systems, and reducing the investment cost.

Energy integration for craft breweries must account for the batch nature of the process; this is specifically true for heat integration which often requires the adoption of storage tanks. When optimising heat recovery options, the batch nature of the brewing process must be systematically analysed by calculating the heat flow of each stage and determining the thermodynamically feasible energy target (pinch point) (Tibasiima and Okullo, 2017). Direct heat recovery is possible when hot and cold streams occur simultaneously by using heat exchangers, requiring a properly designed thermal storage. A detailed pinch analysis for all the hot and cold streams in the beer production process is presented by (Marechal et al., 2013), who investigated the integration of refrigeration cycles, energy conversion technologies and heat pumps, concluding that the selection of the most applicable technologies strongly depends on electricity and natural gas prices.

Similarly, elsewhere a pinch analysis was performed to investigate the feasibility of direct and indirect (solar-thermal) heat recovery options in a medium-scale brewery (250,000 hL/yr) in Scotland (Eiholzer et al., 2017). It was estimated that a 200-kW solar thermal system (300 m^2 evacuated solar collector) could supply 7.7% of the total heat demand and save 38 tons of CO_2 annually, with a payback period of 6.4 yr. Another study demonstrated that solar energy implementation for process heat at temperature levels above 100 °C was applicable in a craft brewery (annual production 8000 m^3) during the summer period in Germany (Wurtzler et al., 2011). 735.5 m^2 vacuum-tube solar panels could provide hot water for the bottle washing machine (32% of equipment demand), as well as for brewing and process water (38% of demand) in a cascading system. The solar thermal system could not be used for the bottle washing machine in the spring/fall period, but it could supply 35% of the space heating demand. In winter, the system could only be used to protect the water in the solar system from freezing (Wurtzler et al., 2011).

Regional and national funding schemes play a critical role in the adoption of solar thermal systems in craft breweries. For instance, in the UK solar thermal systems up to a capacity of 200 kW are incentivised with 0.1 £/kWh for 20 yr, representing a restriction in the total amount of solar heat that can be economically integrated. Although potentially 40% of the hot utility demand could be replaced by solar heat in a medium-sized Scottish brewery, due to the restrictions of the UK Renewable Heat Incentive program only 7.7% was economically feasible

(Eiholzer et al., 2017). Finally, a case study on the integration of solar heat (1 MW) was performed by using concentrating solar panels in a Californian brewery (Kurup and Turchi, 2019). A sensitivity analysis was conducted, identifying project life, tax rate, and panel cost as the most significant parameters.

6.3. Solar energy integration for BSG treatment

Solar energy implementation, either as thermal or PV, can be useful to implement the energy-intensive BSG valorisation pathways described in Sections 4 and 5. More specifically, thermal energy is needed in AD to cover heat dispersion throughout digester walls and, more importantly, to raise feed flow temperature from ambient to mesophilic temperature; electricity need, instead, is minimal (Cottes et al., 2020).

Solar thermal energy can be used to cover the high heat demand for BSG drying when thermochemical technologies or pellet production are the desired BSG valorisation solutions. Thus, solar thermal energy implementation may improve the applicability of innovative methods, which is currently uncertain for craft breweries.

In the literature, there are not many studies on the solar drying of BSG. (Mutlu et al., 2021) reports a pilot plant located in Chiloeches (Guadalajara, Spain), operated solely on solar energy for BSG drying: they investigated improving plant capacity by integrating a biomass boiler by using Aspen Plus simulations. Additionally, techno-economic feasibility analysis indicated that specific solar costs were 3.24 and 6.78 times higher than the specific biomass boiler costs, restricting the expansion of the system using solar energy. (Mosqueda, 2014), instead, compared the performance of prototype solar and biomass energy-powered dryers to improve the shelf life and safe use of BSG as animal feed in the Philippines: it took 5.5–6 h for the solar dryer to reduce BSG moisture content from 71% to 10%. The technical feasibility of solar and conventional electric drying of BSG was compared by Capossio et al. (2022). Although solar drying eliminates the need for electricity consumption, it requires significantly longer process times (345–430 min) compared to traditional dryers (30–85 min), indicating the need for further technology advancements. In the case of craft breweries, the extended process times may still not be a deal-breaker considering the limited volume of generated BSG.

On the other hand, PV integration in craft breweries may allow to cover the electricity demand of the electrical machinery, including the energy-intensive processes (ultrasonication, pulsed electric field, microwaves) implemented as pre-treatment before the extraction of chemical compounds, such as phenols. The possibility to partially or totally cover the electricity request of these advanced technologies through PV can enable their full-scale applicability, even at craft breweries' level.

6.4. Geothermal energy

Although subject to the location, geothermal energy has a great potential to supply heat for breweries either in large-scale district heating applications or in individual projects. Breweries operating on geothermal heat have been reported in the USA, Iceland, and Italy (Cianella, 2022; Lund, 2015; Olden, 2019; Ölverk, 2023; Serengeo Engineering, 2016). A small Italian brewery, Vapori di Birra, located in Tuscany uses heat from a 20 MW geothermal plant (Sasso 2) (Enel Green Power, 2019): the vapour from the district heating system gets to the brewery at about 230 °C and is converted to 136 °C water with a heat exchanger. The utilised water is then returned to the plant for cooling and injection into the subsoil, ensuring a closed loop. Geothermal integration resulted in a 25% reduction in production costs. Although geothermal heating and cooling systems potentially offer several advantages to breweries, there are no scientific reports on this subject.

Fig. 5 recaps the main advantages and downsides of renewable

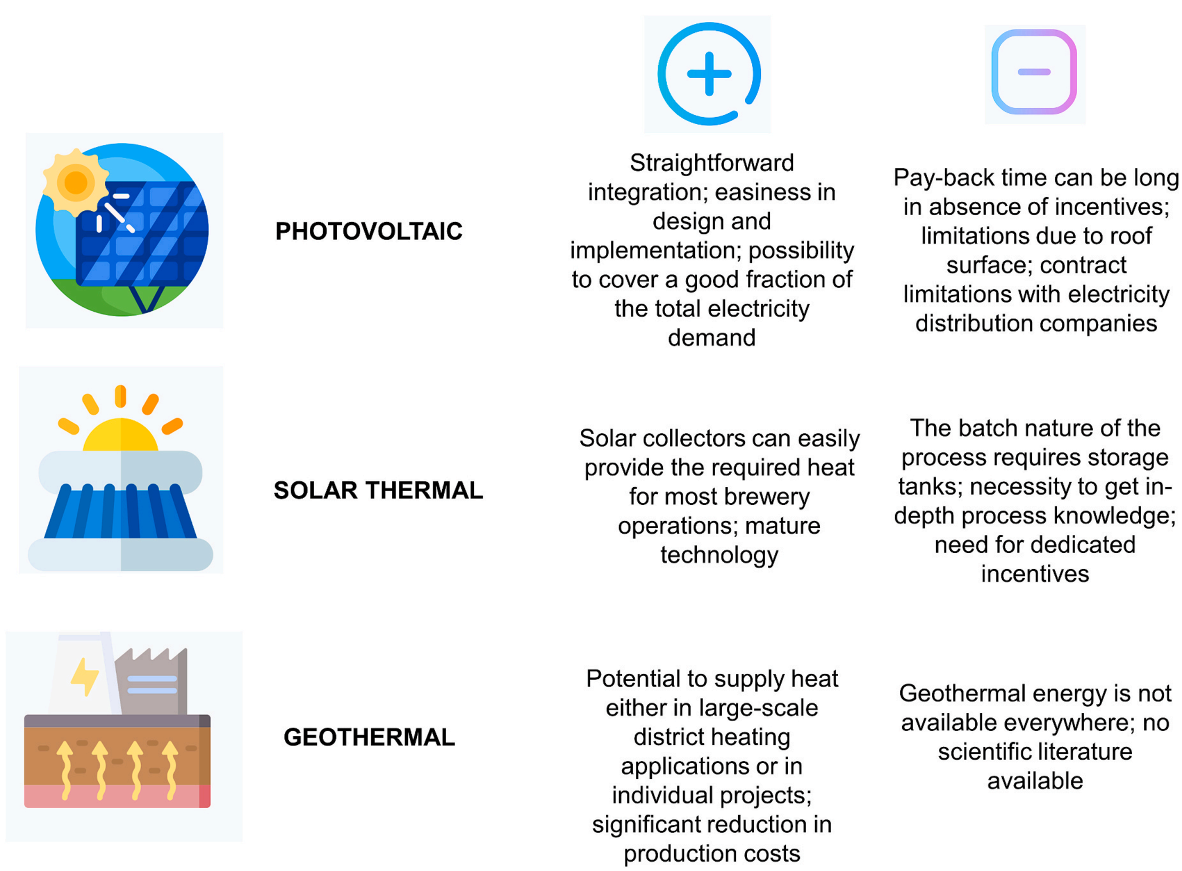

Fig. 5. Advantages and downsides of renewable energy integration in craft breweries.

energy technologies. Further research is needed to move towards a 100% renewable beer production process, especially in craft breweries, however, the wide scientific interest is expected to quickly boost this paradigm shift.

7. Conclusions

In this review, the environmental sustainability of craft breweries was broadly analysed, with a focus on BSG, as the main residue of beer production, and renewable energy integration (PV, solar thermal, geothermal). The possible solutions to enhance craft breweries' sustainability can be compared in a standardised way through LCA and LCC, giving useful insights to decision-makers. The main environmental hotspots of craft breweries are different (and higher) than those of large-scale breweries, so dedicated studies are required. BSG valorisation is fundamental from a circular economy perspective. BSG utilization as animal feed still appears to be the most feasible solution due to its simplicity, especially in developing countries and rural areas, however, the local availability of farms is a limiting aspect in industrialised areas and developed countries, and the economic balance can be uncertain due to the absence of additional income. Alternative mature solutions for BSG management include composting and AD; however, care must be posed to the treatment of BSG alone, due to its high lignin content, limited biodegradability, and generation of unwanted by-products. Other strategies which recently gained interest include thermochemical processes (pyrolysis, HTC, gasification), which allow obtaining biochar or hydrochar with added-value applications, but are limited by the high energy request for BSG drying. Alternative solutions include BSG addition to food or feed to improve the nutritional properties, reducing products' cost while retaining organoleptic properties; BSG reutilisation in the construction sector or composite materials may be feasible only if there exist local industries to valorise it.

Renewable energy can be implemented in craft breweries as PV or solar thermal, the first showing easier applicability, while the latter being limited by the need to thoroughly study the energy consumption profiles and the batch nature of the process. Interest is being devoted to geothermal energy, where available, given its positive impact on the energy balance, despite a lack of scientific studies. Further research is needed to apply LCA and LCC to the alternative BSG valorisation pathways and renewable energy implementation, also considering local factors that may alter the relative impact of each technology, providing a useful ranking of the technologies for decision-makers.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CRediT authorship contribution statement

Matia Mainardis: Conceptualization, Data curation, Investigation, Methodology, Supervision, Visualization, Writing – original draft, Writing – review & editing. **Méabh Hickey:** Data curation, Investigation, Visualization, Writing – original draft. **Recep Kaan Dereli:** Conceptualization, Data curation, Investigation, Supervision, Writing – original draft, Writing – review & editing.

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.

Acknowledgments

Dr. Mainardis acknowledges CAFC S.p.A. water utility for the collaboration in the RTDa project. Dr. Dereli acknowledges Next Generation Energy Systems (NexSys) Programme (SFI/21/SPP/3756) for the support. The icons used for the images were made by Freepik from www.flaticon.com.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.141527.

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