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The missing link of circularity in small breweries' value chains: Unveiling strategies for waste management and biomass valorization

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ABSTRACT

Despite the large quantities and possibilities of reuse of the by-products (solids and liquids) generated by the brewing industry, the proper disposal of these by-products has imposed severe problems for circular and cleaner production transitions worldwide. These challenges are still more salient for the small breweries due to the recognized lack of resources, such as knowledge, finances, and skilled staff. To address this problem, this article aims to identify sustainable strategies for waste management and biomass valorization that can be implemented in the value chain of small breweries. A mixed-method approach was implemented for the data collection and analysis to expand the evidence of the findings, including interviews with 18 small breweries and six specialists in the sector. We found that breweries mainly dispose of the by-products for animal feeding, although industry experts and the specialized literature indicate that at least 21 reuse and recycling alternatives have not been implemented in the value chain. Findings add to the literature five new alternatives informed by companies and six informed by experts for circular and cleaner production realization in small breweries' value chains. Furthermore, the article proposes a novel conceptual model to facilitate waste management and biomass valorization realization in small breweries value chains. Findings provide new insights that complement previous studies to overcome the challenges for waste management and biomass valorization in the sector. The article offers implications for theory, policymakers and managerial practice with repercussions on the production, environmental and financial issues.

1. Introduction

Studies have evidenced the large quantities of by-products, such as brewers' spent grain (BSG), that are generated during the beer production process (Swart et al., 2021; Ortiz et al., 2019; Luft et al., 2019; Lynch et al., 2016; Lee et al., 2015; Johnson et al., 2010). However, the majority of the literature in the area is based on insufficient information or empirical data resulting in the loss of opportunities for cost reduction (Yoo et al., 2021; Campos et al., 2021; Ibarruri et al., 2019; Ivanova et al., 2017), reuse for energy savings in processes, or minimization of solid waste that ends up being destined for landfills (Vendruscolo et al., 2021; Ran et al., 2021; Ortiz et al., 2019). It is noticed that more efficient and sustainable alternatives for small breweries' operations are necessary against the challenges imposed for the appropriate waste disposal and regulatory constraints. In this case, the residues with a significant environmental impact include malt bagasse, trub, and yeast (Su et al., 2021; Garcia-Garcia et al., 2017).

Most importantly, the urgency of studies examining solid waste management and biomass valorization options for the by-products in small breweries value chains occurs because the brewing industry generates large amounts of BSG (Codina-Torrella et al., 2021; Czubaszek et al., 2021; Lynch et al., 2016; Vanreppelen et al., 2014; Fărcaș et al.,

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2014a, 2014b). BSG is the most abundant by-product resulting from the beer production process (Barbu et al., 2021; Ran et al., 2021; Lynch et al., 2016). However, although these solid wastes could be recycled immediately, in practice, they receive insufficient attention from the value chain as a commodity. Frequently, their disposal becomes a problem for companies in the sector, leading to the need to develop non-sustainable alternatives for management and disposal (MMA, 2016). For example, considering that, on average, 85% of brewery waste is BSG (Ivanova et al., 2017), one of the alternatives is the reselling of waste to secondary markets, eliminating the need for disposal (Olajire, 2020).

Reuse and recycling are essential strategies for transforming waste into new valuable resources (Ricciardi, 2020; Graham and Potter, 2015). Furthermore, such strategies enable circular solutions to maintain the value of products and resources for as long as possible (Stelick et al., 2021; Smol, 2019; Rigamonti et al., 2018; Kirchherr et al., 2017; Jawahir and Bradley, 2016). Today, more than ever, it is necessary to expand the potentials of sustainable strategies for underexploited sectors as small breweries value chains to advance the knowledge that results in better decisions for disposal or waste valorization (Yoo et al., 2021; Kral et al., 2019). Therefore, studies addressing aspects of waste management infrastructure (Liu et al., 2017), cleaner production or strategies of production of value-added products from the waste of beer companies are socially and strategically needed (Jaria et al., 2019; Borel et al., 2018).

Another particular aggravating aspect of the beer production process is the volume of production and, consequently, the volume of wastes generated by the sector worldwide. China, the United States, Brazil, Mexico and Germany led the yearly production of beer. For example, China produces approximately 38 million kiloliters of beer per year, the United States 21 million kiloliters, Brazil 14 million kiloliters, México 11 million kiloliters, and Germany 9 million kiloliters per year (Wordlatlas, 2018). Despite these figures, the possibility of market growth (14.4% in 2020) is still significant by analyzing the per capita consumption. Brazil, for example, occupies the 17th position, having an average consumption of 64 L per person/year, while the Czech Republic is the global leader with 144 L per person/year (Sebrae, 2014).

More specifically, the most significant environmental and social concerns regarding the by-products resulting from breweries are related to waste disposal (Sganzerla et al., 2021a,b; Jackowski et al., 2021; Bakan et al., 2021). Even though these can be considered clean residues, as far as activity is concerned and not proactive concerning sustainability (Olajire, 2020; Lucas and Noordewier, 2016). In this context, we hypothesize that developing this sustainable proactivity could bring environmental and societal benefits to the breweries' value chains and borders' value chains. In addition, improving the use of energy and materials to improve production efficiency can increase recycling rates, prevent losses, and favor more sustainable businesses models (Bocken et al., 2014).

From the landscape of the extant literature, this paper assumes that strategies for industrial waste reduction, such as the circular economy, can enable new circular value propositions and biomass valorization in small breweries' value chains. In this regard, cradle-to-cradle strategies can assist breweries in implementing circular solutions (Niero et al., 2016; Mathews and Tan, 2011; Braungart et al., 2007), resulting in benefits for the society (Pauw et al., 2014). Specifically, the exploitation of BSG can be considered a cradle-to-cradle strategy (Toxopeus et al., 2015) since the wastes can be used as raw materials to add value in other production chains. The malt bagasse, for example, is a BSG (Djukić-Vuković et al., 2016) and the most abundant by-product of the brewing process, in the proportion of 20 kg of bagasse for 100 L of beer (Mussatto et al., 2008). However, a critical aspect concerning perishability which prevents bagasse residues from being stored for long periods (Rosa and Beloborodko, 2015). In sum, although some approaches have multiple uses for bagasse residues (Campos et al., 2021; Barbu et al., 2021; Ran et al., 2021), sustainable and effective and easy-to-use strategies of biomass valorization on an industrial scale are still missing (dos Santos Mathias et al., 2014; Swart et al., 2021; Stelick et al., 2021; Aliyu and Bala, 2011) to small breweries' value chains.

Therefore, taking into account the substantive environmental, social and economic challenges involving the disposal of BSG in small breweries value chains, the research question guiding this study examines ***RQ.*** *What are the main alternatives for waste management and biomass valorization of BSG in small breweries' value chains?*

Specifically, this paper aims to identify alternatives that could be immediately implemented for small breweries introducing distinct practical and theoretical contributions to the problem. Our research findings contribute theoretically and empirically to presenting a detailed set of feasible waste management and biomass valorization strategies to minimize the impacts of waste disposal in small breweries. Some alternatives identified influencing not only environmental issues but also economics and society in the value chain of the sector are identified and discussed. The study encourages further practical understanding and theoretical development regarding how small breweries can advance with future technical studies on the benefits that new alternatives for BSG recycling and reuse can offer. The article also offers a platform for new research directions to overcome the challenges for waste management and biomass valorization in small breweries' value chains.

The research is structured as follows. The following section presents the review of the relevant literature on strategies for industrial waste management and biomass valorization in small breweries' value chains. Section three presents the limitations of the current models for waste management and biomass valorization of BSG in small breweries. Section four describes the methodological procedures adopted for the data collection and analysis. The following section details the results obtained in the exploratory case study performed in the sample of 18 small breweries investigated. Section six presents the discussions regarding the findings and research implications for practical, theory-building and society. Finally, section seven ends the study by presenting the conclusions, limitations and avenues for continuity of research in the area.

2. Strategies for industrial waste management and biomass valorization in small breweries' value chains

Some studies on alternatives for the disposal and recycling of BSG mention that solid waste such as malt, after its processing, could be commercialized to third parties generating financial returns. One of the reasons is that this type of solid waste is an important nutrient source (Rosa and Beloborodko, 2015; Fakoya and Van Der Poll, 2013). The current state of knowledge in the field allows us to summarize the main strategies identified in the literature for BSG disposal and recycling into 11 main categories, namely: animal feed, human food, composting, biogas, substrate for mushrooms production, a substrate for the production of enzymes, absorbents, concrete and ceramic material, paper, bricks, bioethanol, Xylitol, Replacement of Wood and Antioxidant. Table 1 presents a general compilation of the data identified during the literature review and the references that cite the identified alternatives.

The use to the animals' feed still is the most typical application indicated in the literature for BSG and other associated residues (Vendruscolo et al., 2021; Mussato et al., 2006). It is considered an excellent animal feed ingredient for cattle, goats, and pigs (Huige, 2006). It can also be used for fish feeding (Kaur and Saxena, 2004). The form in which BSG is used for this type of alternative is generally wet or dry (Öztürk et al., 2012).

It is possible to affirm that there is still no evidence that the animal feed could be fully constituted by BSG, indicating the inclusion of 30% in the proportion for fish feed (Kaur and Saxena, 2004), 40% for bovine feed, and 15% for swine feed (Vieira and Braz, 2009). Animal feed based on BSG, besides being beneficial concerning environmental issues, giving noble purposes to the waste, also contribute to a 45% of reduction in the costs of rural animal feed producers (Aliyu and Bala, 2011).

Table 1
State of the art of literature of alternatives for reuse and biomass valorization of BSG.

Source	Animal feed	Human food	Composting	Biogas	Substrate for mushrooms production	Substrate for enzymes production	Absorbents	Concrete and ceramic materials	Paper	Bricks	Bioethanol	Xylitol	Replacement of wood	Antioxidant
Swart et al. (2021)												*		
Stelick et al. (2021)		*												
Czubaszek et al. (2021)		*												
Yoo et al. (2021)			*											
Codina-Torrella et al. (2021)														*
Vendruscolo et al. (2021)	*		*				*							
Kavalopoulos et al. (2021)											*			
Campos et al. (2021)		*												
Barbu et al. (2021)													*	
Ran et al. (2021)				*										
Su et al. (2021)							*							
Almendiger et al. (2020)														*
Palomino et al. (2016)								*						
Farcas et al. (2014b)		*												
Farcas et al. (2014a)		*												
Rosa and Beloborodko (2015)	*													
Lima et al. (2014)											*			
Fakoya and van der Poll (2013)	*													
Lorenz et al. (2013)				*										
Aliyu and Bala (2011)	*													
Ajanaku et al. (2011)		*												
Acácio et al. (2011)			*	*			*		*					
Pauli (2010)					*									
Vieira and Braz (2009)	*													
Stojceska et al. (2008)		*												
Huige (2006)	*													
Mussato et al. (2006)	*	*		*	*	*	*		*	*				
Russ et al. (2005)										*				
Kaur and Saxena (2004)	*													
Öztürk et al. (2012)	*	*												
Zanker and Kepplinger (2002)				*										
Wang et al. (2001)					*									
Hassona (1993)		*												

Regarding the utilization to prepare human food, Campos et al. (2021) highlight the use of BSG's as a replacement for meat in pork sausages production. Also, cookies from a wet brewery waste can be an interesting alternative from an environmental and economic point of view. Regarding its production feasibility, tests were performed considering the aggregation of the large, medium, and small particles of BSG, and the first two obtained better results when submitted to sensory analysis (Öztürk et al., 2012). In this sense, to maintain the nutritional properties, it is interesting to use a proportion of 6% of BSG instead of the same proportion of conventional flour, highlighting the taste concerning traditional cookies (Ajanaku et al., 2011). Rosa and Beloborodko (2015) discuss the use of BSG in the preparation of cookies in partnerships between breweries and bakeries, generating a financial return for both businesses. Moreover, other approaches to human nutrition are also possible, such as making bread, appetizers, and flakes (Mussato, Dragone and Roberto, 2006; Stojceska et al., 2008; Pauli, 2010). It can be an important nutrient because the malt increases its fiber quantity (Ktenioudaki et al., 2012).

Another alternative for human food is bread production from malt bagasse (Czubaszek et al., 2021). This alternative considers the addition of several proportions of residues in its production (in rations of 5%–30%), increasing the products' nutritional value (Hassona, 1993). The most striking characteristics of this type of bread are the dark color and the sharp taste of beer yeast. This implies that this kind of utilization could be well accepted in terms of sensory analysis despite its darker color (Farcas et al., 2014a). In addition to economic benefits, malt bread can positively affect humans by lowering cholesterol levels (Hassona, 1993) and calories compared to typical flour bread (Farcas et al., 2014b). The production of snacks containing brewing by-products can also be considered an alternative to traditional snacks beers and the production of cereal bars (Stelick et al., 2021). This alternative can benefit those breweries with sales channels offering beer tasting and appreciation for final consumers (Mussatto et al., 2006).

The literature also shows that composting can be an interesting alternative to BSG because it is a rich source of nitrogen and organic materials for soil nutrition. It was also applied to the growth of some vegetables, such as lettuce (Yoo et al., 2021). However, for this purpose, it cannot be disposed of by itself in the soil, but to be efficient, it must be composted and mixed with other items, such as water and other green materials, and a suitable place must be available for mixing (Vendruscolo et al., 2021; Acacio et al., 2011).

Biogas generation was evaluated through life cycle analysis, highlighting that the use of food waste brings advantages to the problems involving climate change issues (Rosa and Beloborodko, 2015). Biogas is generated from the conversion of organic waste (Ran et al., 2021). In this case, the malt bagasse produces 58%–65% methane gas from anaerobic digestion. In addition, malt bagasse can also be added to other wastes for biogas generation, increasing the gas production of these and reducing the time for the process to be completed and the gas has been generated (Acacio et al., 2011). Despite this greater effectiveness, BSG can eventually be limited in relation to the properties of their substrates, so in this case, enzymes can be used to compensate for these limitations (Lorenz et al., 2013). The reuse of biogas for energy generation in the brewery itself is also possible. It can partially support the demand of the industrial plant (Zanker and Kepplinger, 2002), assisting in the generation of energy in a range of 25%–70% of total consumption (Lorenz et al., 2013). It can result in an excellent alternative to economic returns, in addition to the already known environmental returns (Mussago et al., 2006).

Another alternative found is the reuse of BSG to produce substrate for mushroom production (Pauli, 2010). The use of BSG as a by-product for the generation of substrate for mushroom production has been successfully tested in a proportion of 70% of the substrate content. BSG can be used directly to form this substrate. However, due to the high availability of BSG, the greatest financial return ends up being for the mushroom producer and not for the beer producer (Wang et al., 2001). The production of enzymes from BSG comes from the development of bacteria in the decomposition of the substrate. One of the enzymes that can be produced is xylanase, which can be useful for bleaching paper pulp without adding chlorine. Xylanase also improves the digestion capacity of animal silage, and it can improve bakery and alcoholic beverage production. Other enzymes can also be generated from bacteria that can produce antibiotics and other natural products for use in pharmaceutical and agrochemical industries (Mussato, Dragone, and Roberto, 2006). The study of Swart et al. (2021) shows the application of BSG's to produce Xylitol, highlighting the increase of revenues to the firms that use this production alternative.

The literature also shows that using BSG to produce heavy metal absorbers such as chromium cadmium and lead in aqueous solutions has similar results to the use of activated carbon (Su et al., 2021; Vendruscolo et al., 2021). In addition, it has been tested mainly in the textile industry to remove dyes from water. Due to the abundance of BSG, these are a good alternative for this function, having to be combined with magnetic fluids and perchloric acid. The primarily absorbed dyes are the Acid Orange 7 (AO7) and Monoazo Acid. However, further investigations are still needed in this regard, and partnerships between breweries and the textile industry may help assess the economic viability of this alternative (Acacio et al., 2011).

The concrete and ceramic materials production is part of the same brick manufacturing base. The effect of adding 10% malt bagasse increases the porosity of materials and improves their mechanical properties. The main benefit of this alternative is the possibility of reducing the consumption of fuels and raw materials of natural ceramics, which again reduces costs for the producer. In this way, the brewer can also benefit by selling waste as inputs for producing these materials (Palomino et al., 2016). The use of BSG for brick manufacturing was implemented in a proportion of 6% inclusion of BSG in the composition of the brick. The use brings direct benefits by increasing the materials' porosity, which increases the insulation ability, and in proportions of up to 6% do not cause color changes. In addition to porosity, the lower density and the increased strength of the products manufactured with BSG are also noteworthy; however, it is emphasized that it is necessary to avoid the production of bricks with this inclusion during periods of high humidity (Russ et al., 2005). The application of BSG for paper production was also addressed and tested for paper towels and business cards (Mussato, Dragone, and Roberto, 2006). The paper produced in this way has good texture, but for this to occur, the BSG must be bleached in advance and should not constitute more than 10% of the composition (Acacio et al., 2011).

Bioethanol is a product that can be obtained from malt bagasse generating appreciable yields due to the malt bagasse being highly hydrolyzed hemicellulosic without detoxification treatment and nutritional supplementation (Kavalopoulos et al., 2021). Before producing bioethanol, however, the bagasse must undergo pretreatment by the steam explosion method at high temperature and pressure, which can facilitate the access of the enzyme to the cellulose fiber. The yields in ethanol production are 4.2% for fermentation with acid-treated bagasse and 0.75% for fermentation with acid-free bagasse (Lima et al., 2014). Finally, the potential use of BSG's as replacement of 10%, 30% and 50% of the wood in particleboards was researched, and the results show that in the 10% replacement tests, it is possible to obtain products with high dimensional stability and stiffness (Barbu et al., 2021). Another alternative, the use as an antioxidant, indicates the potential of BSG's as biological sources of ingredients for skin whitening cosmeceutical products (Almendinger et al., 2020) and also as a natural antioxidant source to protect food systems against oxidation (Codina-Torrella et al., 2021). In sum, the literature landscape reinforces these topics' relevance for developing sustainable and economic strategies for waste management and biomass valorization strategies so that breweries could reduce the impacts of BSG disposal.

3. Models for waste management and biomass valorization of BSG in small breweries: limitations of the extant literature

The previous models in the extant literature about BSG recycling and reuse were analyzed to comprehend their scope and limitations to address the problem. The first model examined was the Zero Emissions Research and Initiatives (ZERI) model. The proposed model is limited to mention the possibility of reinserting BSG to animal feed (i.e., fish and pigs), producing bread and substrate for mushroom growth, and the biodigestion to produce biogas (ZERI, 2013). A second model analyzed for recycling and reuse of BSG was proposed by Jackowski et al. (2021). The model suggests the possibility to use torrefied BSG's for the combustion and after to heat the water used in the production process. Koroneos et al. (2005) applied life cycle assessment methodology to examine in a case study in Greece. They analyzed the recycling of bottles and scrap glass of breweries and the use of BSG as animal feed. The authors show the related emissions and wastes generated on the beer process affecting the emissions on the atmosphere (Koroneos et al., 2005).

The fourth model examined was proposed in a study conducted in the Southern Brazilian region. Colpo et al. (2021) investigated the reuse of BSG's as human food, animal feed, biogas, biomethane production, concrete, cellulose and as a mixture of wood. The fifth model examined was proposed by Bolwig et al. (2019). Bolwig et al. (2019) investigated how brewers can enhance the circularity of organic waste. They addressed how to use and manage BSG by examining technical options, socioeconomic factors, supply chain issues, and regulatory concerns. Human food (baking ingredients), animal feed, and fuel are the primary BSG reuse and recycling strategies indicated. Despite suggesting a BSG reverse path, the model is limited to suggesting generic alternatives in recognized categories (i.e., human food, animal feed and fuel).

Sganzerla et al. (2021a) conducted a comprehensive literature review, assessing 510 studies related to the use of BSG in biorefineries. The findings indicate that a biorefinery unit might be established to utilize BSG to obtain several valuable by-products fully. Options of technological routes for using BSG include the production of proteins, arabinoxylans, ferulic acid, xylitol, xylose, lactic acid, butanol, biogas, fertilizer, and ethanol. Despite a detailed examination, the model is specific to propose options for BSG valorization in the context of biorefineries. They concluded that "… although there is a great interest in the valorization of BSG, little research in this area is still directed towards possible industrial applications." (Sganzerla et al., 2021a, p. 1983). Kavalopoulos et al. (2021) also propose using BSG for biofuels production in biorefineries as a pathway to mitigating environmental pollution from BSG. The eighth model examined (Lemaire, 2020) analyzed the circularity and future prospects of the Belgian beer brewing industry. Food, feed, fiber, and fuel are among the suggested options for BSG reuse. The study provides a general framework but does not detail specific solutions for each indicated option. Lemaire' study recommends that future studies take a holistic approach to the entire supply chain to identify gaps in circularity loops and more cooperation among the supply chain members. Specifically, it was concluded that "… despite being a very innovative sector, there is room for improvements, as far as circularity is concerned. Especially for higher added-value brewer spent grain (BSG) revaluation alternatives, as well as regarding the origin of the barley and the whole circularity and logistics associated with primary packaging." (Lemaire, 2020, p. 3).

The ninth model examined (Jackowski et al., 2021) investigated strategies for valuing BSG as a solid fuel to be used to generate heat for the brewery production process and as a coloring agent that could replace coloring malt in the production of dark beers. The model's main limitation is its emphasis on thermal energy in applications of low added value. Fillaudeau et al. (2006) investigated the wastewater management issue in beverage production, concluding that water consumption and disposal are still critical issues for sustainability. The findings pointed to the use of BSG to fish feed, fertilizer, biosorbent, and paper as biologic and technical alternatives. The eleventh model (Bakan et al., 2021) analyzed explores the factors required for the shift from a "losses and waste" to a "resources and opportunities" context to maximize the use and valuation of biomass and wastewater and implement technical innovations in firms. The study emphasizes the energy production through fertilizer biodigestion. By exploring options for utilizing typical solid by-products from breweries, Jackowski et al. (2020) asserted that one of the more effective ways to reuse and recycle BSG is to make the BSG processing near the brewery to mitigate transport/environmental impacts. The authors identified five broad BSG alternatives, including fuel, construction materials, extraction, animal and human nutrition, and activated carbon/sorbent.

Ortiz et al. (2019) investigated the feasibility and benefits of including a stage for energy recovery from BSG. They discovered that the BSG gasification process reduces the total volume of residue for disposal, saving approximately 22% of the fossil fuels used in the brewing process when the gas produced is used for heat production in the system.

Sganzerla et al. (2021a) provide a techno-economic evaluation of bioenergy and fertilizer fabrication from anaerobic digestion of BSG. Five techno-economic simulations were conducted by integrating the production of biomethane, electricity, thermal energy, and fertilizer. The simulations results yielded a return on investment of 23.68%, a payback time of 3.76 years, and a net present value of up to 1.5 million USD. Results also showed that the revenue from biomethane and fertilizer was financially beneficial and appropriate for realistic implementations, with a payback time of 3.67 years and an internal rate of return of up to 20%. They conclude that the waste management system based on fertilizer production and bioenergy recovery from anaerobic digestion of BSG is financially viable and beneficial to breweries. Lastly, dos Santos Mathias et al. (2014) present a review of the brewing industry's solid wastes, including BSG, hot trub, and other residues, describing their characteristics, how they are obtained in the brewery processess, composition, and the adoption of the alternative in bioprocesses. Overall, they conclude, BSG "… has current application of greater relevance for animal feed and great potential for its use as a support for growth of immobilized microorganisms in industrial bioprocesses." (dos Santos Mathias et al., 2014, p.8).

The integrative analysis of the limitations of extant models oriented to waste management and biomass valorization of BSG in small breweries reveals interesting insights. First, extant literature is limited in terms of scope. The research to date has tended to focus on restricted conditions, missing a holistic view of BSG recycling and reuse strategies. Altogether, the results show that much of the current literature on BSG pays particular attention to specific contexts (e.g., biorefineries, energy generation), specific processes (e.g., heat production in the system), and well-known alternatives to BSG recycling and reuse. Second, a relatively small body of literature is concerned with the analysis and proposition of high added value strategies to the problems related to eh disposal of BSG. Third, the extant models have failed to address a systemic perspective of the value chain and the collaboration between the supply chain stakeholders. Finally, studies have not investigated strategies for waste management and biomass valorization of BSG based on the cooperation with other value chains sufficiently. As a result, the generalizability of much-published research on this issue is problematic and insufficient research exists examining the reality of small breweries' value chains. The methodological procedures for data collection and analysis are discussed in detail in the next section.

4. Materials and methods

4.1. Research design and context

This research aimed to identify sustainable strategies directed to waste management and biomass valorization of BSG that small companies can implement through breweries' value chains. The methodology used for the development of the work was structured into four main stages: (i) literature review, (ii) interviews with small brewery managers, (iii) interviews with recognized experts in the brewing sector, and (iv) data triangulation that subsidized the discussions of the information identified in the previous three stages.

Initially, we sought the recent and contemporary literature on waste management for the breweries sector, identifying themes that support the research objectives. The strategies related to the circular economy, zero emissions (Kuehr, 2007), and cradle-to-cradle (Toxopeus et al., 2015) were considered. For this research, books and articles published in journals and periodicals were consulted as primary data sources. The definition of the search scope was based on the assumption that these are the recognized strategies that underlie and inform the adoption of sustainable practices in the industry.

From these premises, the research deepens its search around the application and development of practices of reuse of brewery waste, combining the broad concepts of reuse with the specificities of the brewing industry and waste management. Based on the results from the literature, a second, more practical approach was conducted through semi-structured interviews with a group of small Brazilian brewery companies and specialists in the brewing industry. Thus, we sought to identify and compare new recycling practices and disposal of BSG not yet addressed by the existing literature and directed to small breweries' value chains.

4.2. Data collection

Data were gathered from multiple sources at various time points during the research resulting in successive stages of data collection.

4.2.1. First stage of data collection

In the first stage of data collection, the review of the specific literature on waste recycling alternatives in breweries was performed. It was done consulting articles published in journals and conferences available in the Scopus databases (formed by several scientific collections including Web of Science, Interscience, Emerald, Elsevier, Taylor & Francis, and others), and ScienceDirect database. The initial keywords used for the search were *beer, brewery, waste, recycling, reuse*, reutilization*, reoperation* and reapplication*. For objectivity and reliability in this first stage of data collection, we designed the final research protocol (Table 2).

The search resulted in a final selection of 23 relevant studies to be examined (Appendix 1) as a result of the schematic flow of the literature review process implemented applying the research protocol (Appendix 2). The summary of the relevant information from these studies was early presented (see section 2), supporting the literature landscape related to industrial waste reduction as an enabler of new circular value propositions and biomass valorization in small breweries' value chains.

Table 2
Research protocol.

Research Protocol	Description
Research databases	Scopus and ScienceDirect
Standard publication	Peer-review journals and conference papers
Language	Papers are written in English
Data range	The range period was 2005–2019
Search fields	Titles, abstracts and keywords
Search terms	((waste and (beer or brewery) and (recycling or reuse* or reutiliz* or reoperat* or reapplication))
Criteria for inclusion	Studies presenting alternatives to recycle or reuse brewery wastes; peer-reviewed journals
Criteria for exclusion	Studies that did not highlight the alternatives to recycle or reuse brewery wastes; simulation or modelling studies
Data extraction	Manual reading of publications by the research team
Data analysis and synthesis	Content analysis of findings demonstrated on the publications

4.2.2. Second stage of data collection

In the second stage of data collection, primary and secondary data were collected on the current situation of waste disposal for recycling in the brewing market of southern Brazil. Therefore, it can be considered as qualitative research (Saunders et al., 2018) aiming to understand social dynamics and relationships based on non-quantifiable aspects, with an exploratory objective to understand the phenomenon investigated accurately (Robson, 2011). A semi-structured interview protocol was adopted with five questions elaborated by the authors and administered in face-to-face interviews with brewery owners (Appendix 3).

The representativeness of the sample considered and enough generalization of the results were evidenced by the population of companies in the region analyzed. At the time of the study, 98 breweries were officially registered (MAPA, 2016) in the region examined. In the region, the growth rate of breweries was 22.4% in 2020, related to 2019. The eligibility criteria required for companies' participation were primarily be classified as a small brewery. The criteria used to classify the company as a small brewery was the monthly production of less than 10 million liters in total. In addition, for the data analysis, we proposed the stratification of the population of breweries in four geographic regions: Porto Alegre (21 breweries), Sinos Valley (23 breweries), Serra (24 breweries), and other regions (27 breweries). From the first regional classification, three subcategories were established based on the monthly production in liters, namely: (i) from 1.000 up to 15.000 L; (ii) from 16.000 up to 50.000 L and; (iii) above 50.000 L. The exploratory data analysis research sought to identify at least one brewery of each of these three categories within each region.

For data collection, 24 breweries were directly contacted by the research team, being six from each region. As a result, 18 agreed to participate in the interview, representing 18.4% of the region' total brewery population (98). Thus, the final sample explored included four breweries from Porto Alegre, six breweries from Sinos Valley, five breweries from Serra, and three from the other regions of the state (Table 3). According to the needs of data collection, it is considered that the multiple samples examined were sufficient to understand the practices currently adopted to waste management in the small breweries value chain.

Face-to-face interviews with a duration varying between 45 min and 2 h were administered through a semi-structured protocol (Appendix 3), allowing additional relevant information during the interview process. To ensure the validity of the data collection instrument, pre-test validation was conducted with three brewery owners from the sample. After implementing changes to improve the understanding of the questions, the interview protocol was finalized. It was composed of six sections. The first section collected general information on the company and the inputs (raw materials) used in the manufacturing process. In the second section, the company provides information about the destination for 12 types of residues. The third section captures the managers' perception regarding the three largest quantities of residues o be treated. The fourth section identifies the level of understanding of the company regarding the possible destinations for each type of residue listed. The fifth section captures the importance attributed to reusing waste. The last section identifies the intention of implementing a waste management model in the company.

4.2.3. Third stage of data collection

In order to complement the results and validate the findings previously obtained, we performed interviews with six experts in the beer production process (Table 4).

Data collection in this stage was achieved utilizing face-to-face interviews with three experts and a virtual format with the other three. They were requested to analyze and complement the alternatives for reuse of BSG outlined by the 18 small breweries, indicating possible alternatives or extensions to these alternatives. The main questions guiding this stage were: Do you know any other reuse destination that can be given to the waste listed below? If so, could you describe which

Table 3
Small breweries sample profile.

Company	Code	Respondent	Region	Production volume (liters/month)	Total employees
Brewery 01	E1	Owner	Porto Alegre	20.000	6
Brewery 02	E2	Production manager	Porto Alegre	7.000	2
Brewery 03	E3	Owner	Porto Alegre	80.000	8
Brewery 04	E4	Owner	Porto Alegre	4.000	2
Brewery 05	E5	Production manager	Sinos Valley	10.000	5
Brewery 06	E6	Production manager	Sinos Valley	7.000	2
Brewery 07	E7	Owner	Sinos Valley	25.000	10
Brewery 08	E8	Owner	Sinos Valley	2.000	2
Brewery 09	E9	Master brewer	Sinos Valley	30.000	7
Brewery 10	E10	Owner	Sinos Valley	80.000	22
Brewery 11	E11	Owner	Serra	80.000	6
Brewery 12	E12	Master brewer	Serra	6.000	2
Brewery 13	E13	Master brewer	Serra	60.000	10
Brewery 14	E14	Production manager	Serra	16.000	9
Brewery 15	E15	Owner	Serra	6.000	2
Brewery 16	E16	Master brewer	Other Regions	15.000	8
Brewery 17	E17	Owner	Other Regions	500.000	82
Brewery 18	E18	Master brewer	Other Regions	50.000	8

Table 4
Expert profiles.

Experts	Experience in the beer production process	Activities
Expert 1	40 years	Master brewer and owner of a consulting company for breweries in Germany
Expert 2	10 years	Master brewer and owner of a brewing company in Germany
Expert 3	10 years	Master brewer and owner of a brewing company in Germany
Expert 4	20 years	Master brewer in Germany
Expert 5	15 years	Master brewer in Germany
Expert 6	20 years	Master brewer in Germany

ones? The following section describes the procedures adopted for the field data analysis.

4.3. Data analysis

After conducting the interviews, the collected data were consolidated and organized in an electronic spreadsheet. The first category of analysis performed was regarding the profile of the participants. Next, the information was analyzed in the following analytical categories: (i) alternatives for organic waste, (ii) alternatives for the destination of solid waste, (iii) alternatives for the destination of liquid waste, (iv) importance of waste treatment and the companys' intentions to implement these alternatives. The criteria of data saturation were applied for data analysis to coding the categories and information provided by the interviewees. Data saturation in qualitative research refers to how new information reproduces what was stated in existing reports result in a certain degree of generalization of results (Saunders et al., 2018). The sample of participating companies was evidenced to be sufficient due to the repetition of the answers given during the interviews.

Moreover, an additional data analysis process was carried out with brewing specialists. The same interview protocol was applied. However, the questionnaire asked the experts whether they knew any alternatives for recycling BSG in breweries, not necessarily already applied in the regional market. An additional round of interviews was performed with six specialists selected according to the criteria of representativeness of the sector and for convenience. The time available to participate in the research also was considered. In order to obtain insights about practice, the sample of experts included only professionals working in the brewery business during a representative period of time.

The data analysis was carried out based on the protocol for qualitative data as indicated in Bardin (2002) by structuring the analysis process into pre-analysis, exploration of the material, data treatment, inference, and interpretation. In the pre-analysis phase, the interview material was organized to systematize any initial ideas. The answers given by the interviewees could already at this stage enable the formulation of the first hypotheses.

While exploring the material of the interviews, the raw data were analyzed and separated into thematic categories (alternatives for waste management and biomass valorization that can be implemented in the value chain of small breweries) by identifying common characteristics among them. Finally, in the treatment of data, inference and interpretation, tables were developed to comprehend better the information provided. From this basis, the answers given by the interviewees were synthesized and compiled. The results observed are presented in the next section.

5. Results

This section presents the findings from the interviews conducted with the participating breweries and the insights that emerged from these results. It is important to outline that each company was allowed to cite more than one alternative to reuse or dispose of BSG, according to their experience in beer production. Therefore, the number of citations is not limited to the number of breweries interviewed. The results were organized according to the following thematic categories: (i) waste management of organic residues, (ii) waste management of solid and liquid residues, (iii) importance attributed by the small companies and alternatives for waste management, (iv) reasons to implement waste management and biomass valorization strategies, (v) strategies for waste management and biomass valorization indicated by experts.

Table 5
Destinations given by breweries to organic waste.

Organic residues	Destination	Frequency	%
Malt bark	Disposal in the sewer network	2	12.5%
	Granola	1	6.3%
	Animal feed	13	81.3%
	Total	*16*	*100%*
Starch (grinding powder)	Disposal in the sewer network	2	13.3%
	Organic waste	1	6.7%
	Animal feed	12	80.0%
	Total	15	*100%*
Malt bagasse	Animal feed	18	94.7%
	Cake	1	5.3%
	Total	*19*	*100%*
Remains of hops	Disposal in the sewer network	6	33.3%
	Animal feed	5	27.8%
	Effluent treatment	3	16.7%
	Treatment of effluents and after disposal in the sewerage network	2	11.1%
	Effluent treatment and after irrigation	1	5.6%
	Fertilizer	1	5.6%
	Total	*18*	*100%*
Trub	Disposal in the sewer network	6	33.3%
	Animal feed	5	27.8%
	Effluent treatment	4	22.2%
	Treatment of effluents and after disposal in the sewerage network	2	11.1%
	Fertilizer	1	5.6%
	Total	*18*	*100%*
Yeast	Animal feed	8	47.1%
	Disposal in the sewer network	4	23.5%
	Return to the process and after disposal in the sewerage network	3	17.6%
	Fertilizer	1	5.9%
	Return to the process, effluent treatment and after disposal in the sewage network	1	5.9%
	Total	*17*	*100%*

5.1. Waste management of organic residues originated during the beer' production process

Results showed the main destinations identified for each type of organic waste analyzed and the frequency with which they were observed in the breweries. Table 5 summarizes the main alternatives given to BSG. These were divided by types of residues. Outcomes indicated that a variety of responses were observed for each type of residue. Findings showed that although this distinction is evident in the generation of waste in the production process; the disposal is usually done jointly, as is the case with trub, yeast, and hops remain.

The results confirm that the destination for animal feed can be considered the actual main alternative for the organic brewery waste: In 59.2% of the cases, companies indicated this as the final destination. In addition, two companies (12%) also indicated human food products as final destination; in this case, cakes and granola.

We observed that the cooperation terms and agreements between the breweries and the animal producers (farmers) that received the BSG followed the logic of *transferring a waste management problem from one link to another link in the value chain*. Furthermore, we found that no financial compensation from the producers was observed in this transference of residues. That is, animals' producers collect the BSG donated by the brewery without any additional control or formal responsibility.

In the case of destination for human food, it was observed that it is usually associated with commercial business units (e.g. a pub or a factory shop where the by-products are sold) that the brewery runs in parallel with the production of the beer itself. However, if destinations related to human food generate a financial return for the brewer, it is practically impossible to use all the types of residues for this purpose. Consequently, they must choose another complementary alternative. In all the cases analyzed, this complementary alternative was the 'Animal feed' destination.

Table 6
Destinations for solid waste.

Residues	Destination	Frequency	%
Sacks and bags (of malt)	General recycling	11	55.0%
	Shipping to other companies (flower shops)	1	5.0%
	Shipping to other companies (bagging manure)	1	5.0%
	Shipping to other companies (furniture factories)	1	5.0%
	Shipping to other companies (wood sawdust)	1	5.0%
	Shipping to other companies (bagging silage)	1	5.0%
	Shipping to other companies (bagging sand)	1	5.0%
	Shipping to other companies (civil construction)	1	5.0%
	Shipping to other companies (bracket stores)	1	5.0%
	Return to the productive process	1	5.0%
	Total	*20*	*100%*
Glass	General recycling	16	100.0%
	Total	*16*	*100.0%*
Cover	General recycling	16	100.0%
	Total	*16*	*100.0%*
Cardboard	General recycling	15	93.8%
	Boiler	1	6.2%
	Total	*16*	*100%*

Table 7
Destinations for liquid effluents.

Waste	Destination	Frequency	%
Washing water (First category of liquid effluents)	Direct disposal in the sewer network	8	44.4%
	Effluent treatment	6	33.3%
	Treatment of effluents and after disposal in the sewerage network	2	11.1%
	Effluent treatment and subsequent use for irrigation	1	5.6%
	Effluent treatment and subsequent sprinkling in agricultural soil	1	5.6%
	Total	*18*	*100%*
Water (Second category of liquid effluents)	Effluent treatment	7	38.9%
	Direct disposal in the sewer network	6	33.3%
	Animal feed	1	5.6%
	Return to the process and after disposal in the sewerage network	1	5.6%
	Treatment of effluents and after disposal in the sewerage network	1	5.6%
	Effluent treatment and subsequent use for irrigation	1	5.6%
	Effluent treatment and subsequent sprinkling in agricultural soil	1	5.6%
	Total	*18*	*100%*

5.2. Waste management of packaging and liquid effluents

The findings also allowed us to verify the main destinations identified for other solid components used in the manufacture of beer (e.g. packaging), as well as the frequency with which each destination was verified (Tables 6 and 7).

The synthesis of results in Table 6 shows that most solid waste is destined for general recycling, while for glass and lids, this is the only alternative implemented.

In the case of cardboard waste, the alternative of burning it in the boiler supplying energy to the factory was also observed. It is a simple alternative but with an associated environmental impact that should be taken into account. Malt bags present more diverse alternatives such as reuse within the process itself and shipping for reuse by other supply chains.

Table 7 summarizes the destination identified for each of the investigated liquid effluents.

The destination analysis given to the liquid effluents distinguishes between general wastewater and water used to wash the tanks in the production process. In the case of washing water, 44.4% of the breweries dispose of it directly in the sewage network, without any type of treatment of these effluents, while the remaining breweries (55.5%) treat these effluents further. Within the group of companies that treat the effluents, 44.4% make the treatment process only after disposal. Findings also showed that approximately 5.6% treat the effluents for use in the irrigation of plantations and 5.6% sprinkling agricultural soil. In the case of water discarded from the process, the destinations are similar to those presented for washing water, but 5.6% of breweries also use water for animal feed.

5.3. Importance and priorities for waste management of BSG

The managers and owners of breweries interviewed were asked about the degree of importance and priority that should be given to the treatment of waste generated during the production process. When asked which type of residue they considered most critical and should receive further treatment, 55% of those interviewed indicated that malt bagasse should be the first waste to be prioritized in future reuse initiatives, and for 33% of the companies, water reuse would be a priority. Additionally, some companies prioritized packaging glass (4%), yeast (4%), and trub (4%).

In order to understand the alternatives for the waste treatment indicated by the companies, the main needs cited by the managers were summarized. In this case, we observed that 48.5% of the reuse demands presented by breweries are related to malt bagasse, 33.5% are related to water, 11.5% to yeast, and finally, glass and trub shared 3.5% of mentions. When asked about the motivations for the reuse of residues, the interviewees were motivated by environmental concerns (E3, E8, E9 and E18), new possible sources of revenue and financial impact on the company (E4, E6, E11, E13, E15) or both, i.e. environmental and financial issues (E12, E16, E17). Overall, the findings indicated that most companies understand that the reuse of residues is an important aspect to be considered in the value chain.

5.4. Reasons to implement waste management and biomass valorization strategies

The managers were asked to indicate whether the enterprise considered implementing a generic model for waste reuse and BSG recycling. We were interested in confirming the companies' disposition to proceed with the implementation of any of the alternatives mentioned during the interviews. Our findings showed that the overall response to this question (Would you consider implementing a generic model in the company for waste management and reuse of BSGs ?) was positive. Representative statements confirmed that:

"*Yes, since malt is very rich in nutrients and should be used in human food, not only in animal (E7).*"
"*Yes, but with low volumes, it is very difficult to give more noble destinations (E8).*"
"*Yes, there is always the possibility of some implementation to improve the reuse process, provided it is feasible (E10).*"

Another interesting response to this question included,

"Yes, as long as it brought benefits to the day-to-day business of the factory, economy or being in compliance with environmental standards (E2)."

In general, the content analysis of findings demonstrated that all companies interviewed considered implementing waste reuse or recycling alternatives important for the company. In addition, the vast majority of companies demonstrated that a generic model assisting small breweries with waste reuse or recycling alternatives could represent an important managerial instrument to the company if it was economically feasible.

5.5. Strategies for waste management and biomass valorization indicated by experts

The research carried out with experts brought complementary results to the insights obtained with the brewers' specialists. Specialists were asked to suggest other alternatives to the reuse of waste and recycling used by other companies at the national and international level within the brewery business. The thematic analysis of the answers indicated the following alternatives: animal feed, human food (especially pizza dough, bread, cookies, appetizers, meatballs, and cereal bars), fertilizer for plants, biogas, yeast capsules from the brewing process, and substrate for the production of mushrooms.

Similar to the results identified in the interviews with brewing companies, the research results with experts brought new alternatives not explicitly mentioned in the literature. In this sense, a more comprehensive range of new alternatives were identified. The main new ones include pizza dough, meatballs, cereal bars and brewers' yeast capsules. These new possibilities expand the range of alternatives that breweries can adapt and increase the value of their waste by turning it into new products. The integrated discussion and implications of these findings are examined in the next section.

Table 8
Summary of alternatives for waste management and biomass valorization of BSG.

Alternatives		Literature	Small breweries	Experts
1	Animal feed	*	*	*
2 (Human food)	Cookies	*		*
	Bread	*		*
	Aperitif	*		*
	Flakes	*		
	Cake		*	
	Pizza dough			*
	Meat dumpling			*
	Cereal bar			*
	Flour		*	
	Waffle		*	
	Meatball		*	
	Brownie		*	
3	Fertilizer	*		*
4	Biogas	*		*
5	Substrate for mushrooms production	*		*
6	Substrate for enzymes production	*		
7	Absorbents	*		
8	Concrete and ceramic materials	*		
9	Paper	*		
10	Bricks	*		
11	Bioethanol	*		
12	Beer yeast capsules			*
13	Xylitol	*		
14	Replacement of Wood	*		
15	Antioxidant	*		

5.6. Synthesis of results for waste management and biomass valorization of BSG

The summary of the main research results provide some interesting insights. First, it was observed that while the literature in the area and the experts interviewed indicated a set of 21 opportunities for the transformation of waste into new solutions, only the application for animal feed and some human food alternatives are currently used by the companies examined (Table 8).

Second, the results indicate that, regarding human food possibilities, new alternatives highlighted by the breweries are the production of cakes, flour, waffles, meatballs or brownies. To the best of our knowledge, this possibility of application of BSG is not explored in the extant literature. It is possible to hypothesize that the alternatives used in human food can be considered an incremental innovation in the production process.

Third, findings also unveil novel insights and advances in knowledge from the outcomes of the expert interviews. For example, experts indicated new opportunities for the use of BSG in human food, such as the production of pizza dough, the replacement of flour in meat dumplings, and the production of cereal bars from dried BSG. Moreover, beer yeast capsules, a product used as a food supplement, is also noteworthy. These new opportunities may reduce beer production' environmental and climate impact while ensuring fair economic returns for farmers and brewing companies. The following section presents the discussion and the original research implications for waste management and biomass valorization.

6. Discussion

This research attempted to identify sustainable strategies for waste management and biomass valorization of BSG to the brewing industry value chain. Overall, the findings offer distinct insights supporting the argument that several alternatives for the appropriate solid waste management and biomass valorization are still not recognized by the managers or even mentioned in the extant literature in the area. Furthermore, we found that, generally, there is a relevant knowledge gap between the strategies that can be adopted to improve the destination given to the BSG and the strategy adopted in practice by the analyzed breweries. Our findings also complement previous related studies in the field (Yoo et al., 2021; Codina-Torrella et al., 2021; Vendruscolo et al., 2021; Olajire, 2020; Hassan et al., 2020; Ricciardi et al., 2020; Ortiz et al., 2019; Aliyu and Bala, 2011), providing additional evidence for solid waste management alternatives to the sector.

"It is likely that, in upcoming years, brewer's spent grains will not be considered as a by-product, but as a desirable raw material for various branches of industry" (Jackowski et al., 2020, p. 1). The research findings show that, among the strategies for industrial waste reduction, the circular economy has demonstrated the potential to enable new circular business models by transforming the loss of resources and increasing the efficiency of their use (Jackowski et al., 2021; Sganzerla et al., 2021a,b; Bolwig et al., 2019; Witjes and Lozano, 2016; By, Bernard and Sloan, 2016; Ghisellinim et al., 2016; Naustdalslid, 2014).

This study found that the infusion of closed-loops based on reuse, remanufacturing and recycling (Ghisellini et al., 2016; Lieder and Rashid, 2016) in small breweries' value chains can assist the companies in overcoming challenges for waste management and biomass valorization and enable new sustainable business models. This finding implies that, given the significant volume of production and waste generated by the sector, the breweries' value chains play an important role in society to achieve an ecological balance (Jawahir and Bradley, 2016).

Taken together, the findings provide valuable insights to the field, addressing some knowledge gaps related to the biomass valuation and waste management in breweries value chains (Hassan et al., 2020; Ibarruri et al., 2019; Fakoya et al., 2013; Farcas et al., 2014; Goberna et al., 2013).

Regarding alternatives not directly related to food, our study depicts that both experts and the literature highlight the possibility of biomass valorization for the production of bioproducts according to the possibilities of each brewing company, taking into account the possibility of new products with high added value. These findings make positive contributions that can help to address persistent knowledge gaps understand the potential industrial applications of high added value of BSG (Sganzerla et al., 2021a; Lemaire, 2020; Ibarruru et al., 2019; Djuvic-Vukovic et al., 2016; Nigam, 2017).

The research has also shown that the total reuse of bagasse waste may be attractive due to the sectors' reduction of environmental impact (Mussatto et al., 2008), although in the case of the reuse in the production of food (e.g., bread and other bakery products) it requires the customers' acceptance (Ktenioudaki et al., 2012). In addition, although the benefits of these residues for human and animal health are recognized, one of the main problems for the reuse on an industrial scale is related to deterioration in a short period (Robertson et al., 2010). Consequently, some specific strategies could be adopted to prevent the deterioration. The first strategies include compaction and subsequent drying within the brewery production, which can reduce the volume of water by about 20%. Nevertheless, the investments in technology and process to create specific product lines in the firm for drying processes still makes it a remote possibility for small microbreweries, especially those operating in underdeveloped countries (Santos et al., 2003).

Lastly, the integrative findings of the paper also imply that the use of BSG should be considered by small breweries' value chains after chemical treatment (Hassan et al., 2020), avoiding the risk of food contamination (Pérez-Bibbins et al., 2015). Specifically, the findings offer some novel insights and have implications for policy, practice and theory-building to the research on waste management and biomass valorization in small breweries' value chains, as discussed in the following sections.

6.1. Implications for waste management and biomass valorization

The findings add to a growing body of literature on waste management and biomass valorization in breweries, suggesting various alternative biotechnological applications to the by-products resulting from the production process. The main alternatives included biogas, bioethanol, and substrates. A practical implication of these outcomes is that BSG can be considered a possibility to replace other raw materials in various industrial applications.

Actually, some studies have promoted BSG utilization mainly via biogas (Malakhova et al., 2015), bioethanol (Wilkinson et al., 2017), and soil additive (Yoo et al., 2021). Aligned with these categories of application, Xiros and Christakopoulos (2012) added the possibility of using BSG to produce antioxidants, xylitol, arabitol, and lactic acid.

From the integrative findings, small breweries' value chains could have a set of alternatives that could be implemented to minimize the impacts of uncontrolled disposal of waste from their operations. Based on our summarized findings (Table 8), we introduce a novel conceptual model that organizes and structures the most salient alternatives for waste management and biomass valorization (Fig. 1).

The conceptual model proposed has important implications for developing new techniques and alternatives that generate environmental benefits and economic advantages for small brewing companies. Specifically, the conceptual model proposed organizes circular relationships for waste management and biomass valorization based on the classification of the 9R's (Kirchherr et al., 2017). According to the authors, is it possible to Recover (R9) material through incineration; Recycle (R8) to obtain the same or lower quality; Repurpose (R7) a discarded product giving it a different or new function; Remanufacture (R6) parts of the discarded product in a new product with the same function; Refurbish (R5) an old product by updating it; Repair (R4) a defective product to be used in its original function; Reuse (R3) of a discarded product by another consumer in its original function; Reduce

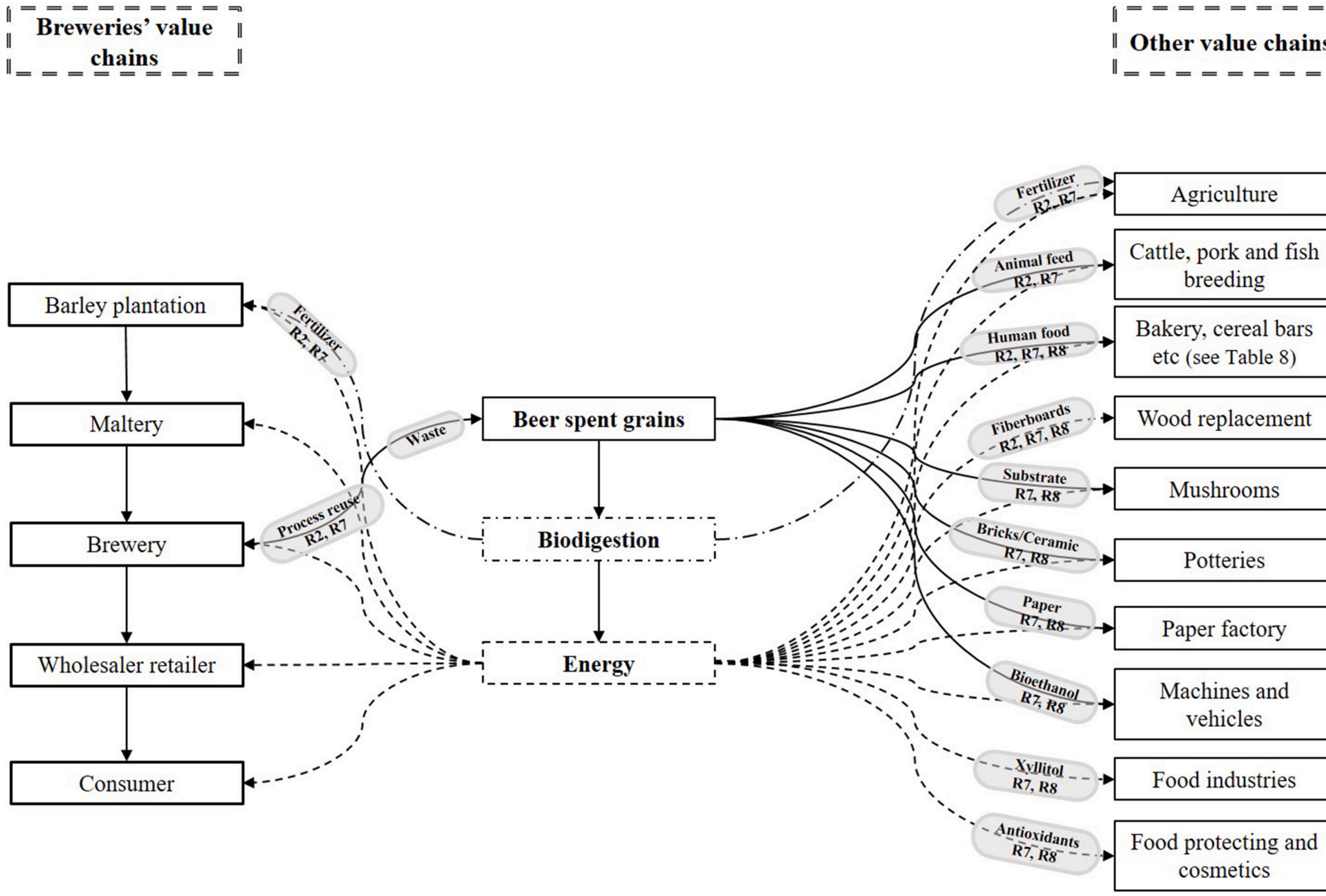

Fig. 1. The conceptual model for waste management and biomass valorization in small breweries value chains.

(R2) the consumption of natural resources and materials in the production process; Rethink (R1) to intensify product use; and Refuse (R0) offering a radically different product with the same function or abandoning an original product's function.

The looping indicated in the model as a "Process reuse" can be simultaneously considered as an R2 (Reduce) and an R7 (Repurpose) strategy. This implies that the reuse of BSG in the beer production processes and raw material for soil fertilization could be used as a promising alternative in barley plantations and other agriculture products. Additionally, the use of BSG for animal feed (e.g. cattle, pigs and fish) can also generate sustainable alternatives for waste management and biomass valorization based on R2 and R7 principles in the value chain. A practical implication is that these strategies can be considered the first step to emissions reduction in small brewery companies and craft beer production processes (Shin and Searcy, 2018).

The model also proposes other reuse and recycling alternatives in the value chains of other industries, namely human food, as a substrate for fertilizing mushrooms, bricks, ceramics, paper production, and bioethanol. The closed loops R7 (Repurpose) and R8 (Recycle) can generate sustainable alternatives for waste management and biomass valorization in the value chain, resulting in opportunities to improve the interactions of small breweries with the environment and society (Argent, 2018). Comparing the extant literature with the proposed model offers a unique methodological proposition based on an integrative set of 26 alternatives to different value chains. Moreover, the model clarifies the possibility of producing energy from BSG and reusing it in the value chain of breweries. In contrast with the extant models that present specific opportunities but are not so profoundly explored (see section 3), the proposed model, for example, suggests the division of human food into 12 alternatives like cookies, bread, flour, etc.

Furthermore, our analysis consolidates emerging research patterns that address persistent lacks of the literature. The landscape from literature addressing the issues concerning waste management and biomass valorization of BSG in small breweries show that the generalizability of the findings is still inconsistent. First, extant literature is limited in scope, paying particular attention to specific industrial contexts, i.e. biorefineries, energy generation (Sganzerla et al., 2021a; Kavalopoulos et al., 2021), specific processes, i.e. heat/energy production (Jackowski et al., 2021; Bakan et al., 2021), as well as others well-known alternatives to BSG recycling and reuse (Swart et al., 2021; Stelick et al., 2021; Czubaszek et al., 2021; Campos et al., 2021; Barbu et al., 2021; Ran et al., 2021; Su et al., 2021; Yoo et al., 2021; Lemaire, 2020 Bolwig et al., 2019; Jackowski et al., 2020; dos Santos Mathias et al., 2014). Second, there is a small body of literature examining higher added value strategies to the problem. Third, the extant models have failed to address a systemic perspective of the value chain and the collaboration with the supply chain. Fourth, studies have not investigated strategies for waste management and biomass valorization of BSG sufficiently based on the cooperation with other value chains close to the breweries operation. Finally, findings from the comprehensive literature review in the area have shown that the most typical use of brewer's yeast is in animal feed and human nutrition (dos Santos Mathias et al., 2014) and that despite widespread interest in this theme, the scarce research on the topic is still focused on potential industrial uses (Sganzerla et al., 2021a). In sum, the proposed model constitutes a guideline for small breweries to facilitate the implementation of strategies for waste management and biomass valorization of BSG.

Therefore, we outline that the empirical findings obtained in the research and the conceptual model developed to offer key practical and managerial implications. First, small breweries and practitioners can use the model to identify new sustainable strategies and opportunities for waste management and biomass valorization within the value chain in which they operate or in other value chains. Second, managers and owners of small breweries can re-evaluate the current strategies used in the company and eventually enhance them considering the closed loops indicated in the model. Third, the research positively contributes to filling the persistent knowledge gaps and challenges in small breweries to implement waste management practices.

Considering the limited exploration of alternatives identified, e.g. emphasizing animal feeding and disposal in landfills, the research outcomes open possibilities for advancing the knowledge on sustainable strategies for the brewery value chain responding to the calls from recent literature (Olajire, 2020; Hassan et al., 2020; Ricciardi et al., 2020). Some of the insights emerging from the research provide value chain benefits for small brewing companies that usually have little availability of tools and information to help them adopt sustainable alternatives in practice in their operations (Campos et al., 2021; Kavalopoulos et al., 2021; Schaltegger et al., 2012). Thus, the sustainable alternatives compiled in this study can be used to start cleaner production programs in small breweries value chains. Large brewery companies can also benefit from our results to enhance their waste management practices. The theoretical contributions are discussed in the following section.

6.2. Theoretical implications

This study supports the theory on waste management and biomass valorization in small breweries presenting conceptual modelling of the value chain and strategic circular interactions with other value chains (Fig. 1). This conceptual model may represent a reference artifact to drive small breweries towards more sustainable management of waste and biomass, highlighting potential circularities. "… due to the circular economy trend of upcycling agro-food wastes, BSG is likely to be used in numerous branches of industry as well as in agriculture (Bolwig et al., 2019, p. 10, p. 10).".

Waste management is one of the significant problems in the world today. To prevent waste from being taken to the landfill, there are management systems to obtain benefits from it instead; this process is denominated as being valorization of residues/waste. In this paper, the valorization of the most critical residue in the supply chain of beer production has been addressed and discussed, providing essential information about how to give it a second useful life. Being able to create a robust circular economy in which zero waste is reached is hopefully achievable in the future, and it also strongly depends on the small entities and organizations. Although their general positive impact might seem marginal, small enterprises such as small breweries may play a key role in supporting more sustainable waste management programs. Indeed, the needing for a paradigm shift in circular thinking at the micro-level has also been recently highlighted in the scientific literature (Brendzel-Skowera, 2021; Rizos et al., 2016). Most importantly, this article contributes to the notion that the "practical implementation of the 'Reduce, reuse, recycle' approach certainly contributes to implementing the rules of the circular economy in the brewing industry" (Jackowski et al., 2021, p. 12).

This paper not only informs them about the potential alternatives for waste management of BSG but also highlights the ones that should be further examined as currently, the companies support just a few of them (e.g. animal feed without relevant added value). In this context, the information generated by this study represents a sort of theoretical guideline to reveal potential alternatives for more sustainable waste management in beer companies. Overall, from a practical point of view, the findings of this study and the insights generated are of substantial interest to different stakeholders such as beer producers and consumers and policymakers aimed to support the Circular Economy Action Plan (CEAP, 2020).

6.3. Implications for society and policymakers

Societal impact refers to the effect of research beyond academia or the effect of change experienced by society from that research. In this context, this paper is particularly relevant as it relates to some of the UN's Sustainable Development Goals (SDGs) (UN, 2015). The SDGs cannot be met unless waste management is addressed as a priority (Elsheekh et al., 2021). While the global population is expected to substantially increase in the coming years (FAO, 2021), a simultaneous effort will be urgently needed in order to decrease food losses and waste sustainably. The potential valorization of biomass in small breweries' presented here represents a step forward in this direction. This is because "… BSG could ensure 'green' energy production in the range of 4.5 and 7.0 million MJ/year if the European BSG potential is fully valorised." (Kavalopoulos et al., 2021, p. 1). The alternatives shown in this study directly contribute to society and policymakers as they lay the groundwork for supporting the circularity of materials and reuse of natural resources in small breweries. Indeed, the Circular Economy is a growing topic in our societies and a well-established goal of our political institutions incorporating different pillars such as reduction, reuse and recycling of resources. This is especially true in the food and agricultural sectors (Bigdeloo et al., 2021). Thanks to our analysis, policymakers may realize that at present, animal feed is basically the main and basically single alternative for the organic brewery waste (Table 5).

Therefore, the new alternatives for circular and cleaner production realization in small breweries' value chains revealed from this study should be carefully evaluated and finally supported. From this point of view, our research can contribute to spreading knowledge and key information of social interest. This cognitive process is expected to imply direct benefits within our societies and stimulate further research advancements. Indeed, information embodied in this study may be used to enlarge the scope of this analysis.

While our study confirms that there is room to develop new alternatives for waste management and biomass valorization in the brewery sector, future advancements are called for looking at these new potential solutions in greater detail and from different perspectives. For instance, our findings can constitute a starting point for environmental or economic impact assessment analysis' such as Life Cycle Assessment or Life Cycle Cost in which the alternatives presented here are assessed and compared with the business as usual scenario, thus supporting the decision-making process (De Menna et al., 2020). Again, analyses evaluating the potential circularity of different waste management systems and biomass valorization in terms of the market for recycled products is also encouraged (Arneil et al., 2013). Overall, the findings presented here can, directly and indirectly, contribute to society and policymakers to move toward more sustainable waste management policies for specific industrial sectors, such as the case of breweries' value chain and the beverage sector as a whole. In the next section, the conclusions, limitations and future research agenda are presented.

7. Conclusions and future research agenda

Drawing from the challenges faced by small breweries, this research examined sustainable strategies for waste management and biomass valorization in the sector, focusing on BSG impacts. In summary, the results contribute with several insights to our understanding of how to make the value chain of small breweries more sustainable. In this research, three primary sources of data to examine the problem were considered. The first was the empirical-based literature in the area, the second was the perspective and opinion of managers and owners of small breweries and the third was the vision of experts.

The major finding observed was that, although several alternatives for waste management of BSG are mentioned in the literature, and by experts in the area, they are underexplored in the companies examined. We found that the companies destine the majority of the residues for animal feed without any added value or valorization of biomass. While, on the one hand, the destination for animal feed cannot be considered as a significant problem for the sector, on the other hand, several other sustainable alternatives exist and could be implemented. The proposition of alternatives has been exposed in our research and can improve the circularity of materials and reuse of natural resources in small breweries' value chains. Further analyses are expected to investigate better the alternatives presented in terms of potential environmental impact reduction and financial compensation at different scales.

The research also contributes to the literature. First, the findings elicited new alternatives for waste management and biomass valorization for breweries not mentioned previously in the literature. Second, this is a pioneer study in this area to indicate closed-loops along with the value chain of small breweries. Third, to the best of our knowledge, this is the first study to propose a conceptual model for waste management and biomass valorization in small breweries value chains integrating sustainable alternatives in other value chains. Finally, the model proposed represents a research effort to build a more systematic development of sustainable strategies for small breweries dealing with proper waste disposal.

Before implementing new BSG reuse and recycling alternatives, we recommend that brewing industries organize the internal processes and prepare the company for the consequent organizational changes in culture and operational practices. We also claim that the practical insights achieved in this study can be incorporated into the extant literature in the area. This is because new recycling alternatives, not sufficiently explored, can extend the current knowledge of practitioners and academics in the field of waste management.

In general, therefore, it is possible to conclude and affirm that the research on this theme is still in its first stages of exploitation, and plenty of under-investigated areas exist. For this reason, specific research avenues are recommended for enlarging this important research stream. Among these, we recommend that further research should be developed in the following main directions:

- First, we recommend that future studies should deepen technical analyses related to clean energy, such as the generation of biogas, biofuels, and electricity from the waste of the beer production chain.
- Second, we encourage further studies that develop models and methods to assist small breweries in implementing waste management practices.
- Third, it is recommended that other studies attempt to enlarge this research to identify other alternatives are currently used in breweries in other regions and contexts.
- Fourth, the findings allowed us to highlight the need for knowledge consolidation on waste management challenges in developing economies, where legislation and control are generally less robust when compared to other well-developed economies.
- Finally, we suggest additional research to confirm the environmental, economic and social advantages of the alternatives discussed in the paper.

Overall, this study encourages further understanding and development of the theory on biomass valorization and solid waste management in small breweries value chains.

CRediT authorship contribution statement

Samuel Vinícius Bonato: Conceptualization, Data curation, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing. **Diego Augusto de Jesus Pacheco:** Writing – original draft, Writing – review & editing, Investigation, Methodology. **Carla Schwengber ten Caten:** Supervision, Funding acquisition, Methodology, Project administration, Resources. **Dario Caro:** Writing – review & editing, Writing – original draft.

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.

Appendix 1

Table A
Selected publications.

Author (s)	Title	Journal
Swart et al. (2021)	Techno-economic analysis of the valorization of brewers spent grains: production of xylitol and xylo-oligosaccharides	*Journal of Chemical Technology & Biotechnology*
Stelick et al. (2021)	Impact of sustainability and nutritional messaging on Italian consumers' purchase intent of cereal bars made with brewery spent grains.	*Journal of Food Science*
Czubaszek et al. (2021)	Baking properties of flour and nutritional value of rye bread with brewer's spent grain	*LWT*
Yoo et al. (2021)	Effects of brewer's spent grain biochar on the growth and quality of leaf lettuce (Lactuca sativa L. var. crispa.)	*Applied Biological Chemistry*
Codina-Torrella et al. (2021)	Brewing By-Products as a Source of Natural Antioxidants for Food Preservation	*Antioxidants*
Vendruscolo et al. (2021)	Brewery spent grain: a potential biosorbent for hexavalent chromium	*Journal of the Institute of Brewing*
Kavalopoulos et al. (2021)	Sustainable valorization pathways mitigating environmental pollution from brewers' spent grains	*Environmental Pollution*
Campos et al. (2021)	Quality measurements of cuiabana-type pork sausages added with brewing by-product flours	*Meat Science*
Barbu et al. (2021)	Potential of Brewer's Spent Grain as a Potential Replacement of Wood in pMDI, UF or MUF Bonded Particleboard	*Polymer*
Ran et al. (2021)	Effects of brewers' spent grain protein hydrolysates on gas production, ruminal fermentation characteristics, microbial protein synthesis and microbial community in an artificial rumen fed a high grain diet	*Journal of animal science and biotechnology*
Su et al. (2021)	Recycling of Brewer's Spent Grain as a Biosorbent by Nitro-Oxidation for Uranyl Ion Removal from Wastewater	*ACS omega*
Almendiger et al. (2020)	Malt and beer-related by-products as potential antioxidant skin-lightning agents for cosmetics	*Sustainable Chemistry and Pharmacy*
Palomino et al. (2016)	Production of ceramic material using wastes from brewing industry	*Key Engineering Materials*
Farcas et al. (2014b)	Brewers ' spent grain - a new potential ingredient for functional foods	*Journal of Agroalimentary Processes and Technologies*
Farcas et al. (2014a)	Nutritional properties and volatile profile of Brewer's spent grain supplemented bread	*English Biotechnological Letters*
Rosa and Beloborodko (2015)	A decision support method for the development of industrial synergies: case studies of Latvian brewery and wood-processing industries	*Journal of Cleaner Production*
Lima et al. (2014)	Study of the production of bioethanol from malt bagasse	*Blucher Chemical Engineering Proceedings*
	Integrating ERP and MFCA systems for improved waste-reduction decisions in a brewery in South Africa	*Journal of Cleaner Production*

(*continued on next page*)

Table A (*continued*)

Author (s)	Title	Journal
Fakoya and van der Poll (2013)		
Lorenz et al. (2013)	Current EU-27 technical potential of organic waste streams for biogas and energy production	*Waste Management*
Aliyu and Bala (2011)	Brewer's spent grain: a review of its potentials and applications	*African Journal of Biotechnology*
Ajanaku et al. (2011)	Functional and Nutritional Properties of Spent Grain Enhanced Cookies	*American Journal of Food Technology*
Acácio et al. (2011)	Business study of alternative uses for brewers spent grain	*Illinois Institute of Technology*
Pauli (2010)	The Magic of Beer	*Journal of Cleaner Production*
Vieira and Braz (2009)	Barley bagasse in Animal feed	*Electronic Magazine Nutritime*
Stojceska et al. (2008)	The recycling of Brewer's processing by-product into ready-to-eat snacks using extrusion technology	*Journal of Cereal Science*
Huige (2006)	Brewery By-Products and Effluents	*Handbook of Brewing*
Mussato et al. (2006)	Brewers ' spent grain: generation, characteristics and potential applications	*Journal of Cereal Science*
Russ et al. (2005)	Application of spent grains to increase porosity in bricks	Construction and Building Materials
Kaur and Saxena (2004)	Incorporation of brewery waste in supplementary feed and its impact on growth in some carps	*Bioresource Technology*
Öztürk et al. (2012)	Effects of brewers ' spent grain on the quality and dietary fibre content of cookies	*Journal of the Institute of Brewing*
Zanker and Kepplinger (2002)	The utilization of spent grains in the brewery integrated system	*Brauwelt*
Wang et al. (2001)	Biological efficiency and nutritional value of Pleurotus ostreatus cultivated on spent beer grain	*Bioresource Technology*
Hassona (1993)	High fibre bread containing Brewer's spent grains and its effect on lipid metabolism in rats	*Die Nahrung*

Appendix 2

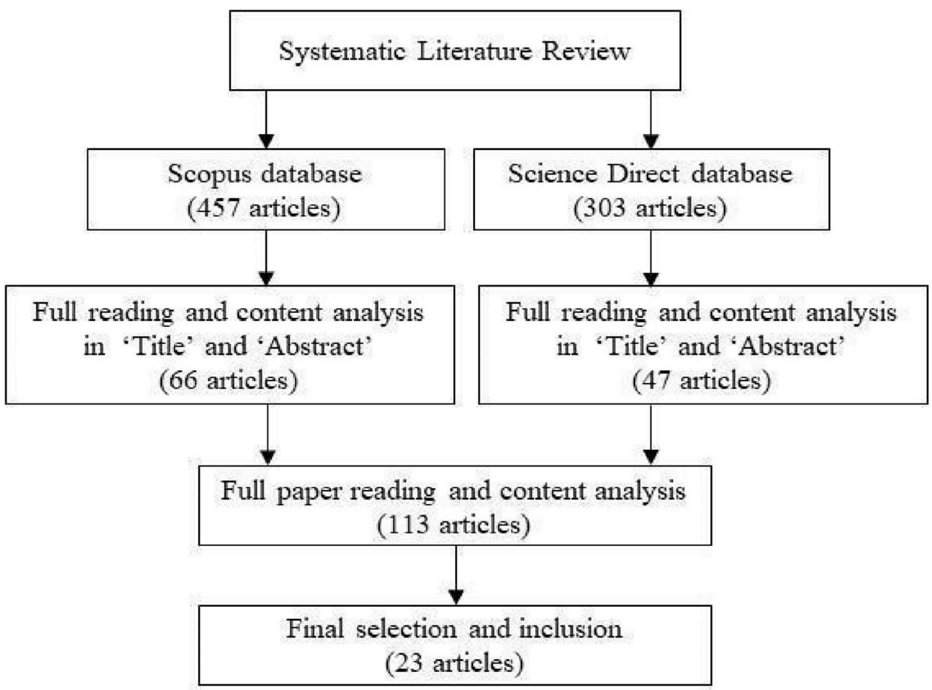

Fig.1Flow diagram of the literature review process.

Appendix 3

Semi-structured interview protocol

I. Enterprise information.

Company (optional):

Number of employees:

Monthly production (liters):

Inputs (raw materials) used in the production process:

II. Among the wastes from the brewing process listed below, what destinations are given to them today?

Type of residue	Destination given by the company after manufacturing
Malt bark	
Starch (grinding powder)	
Sacks and bags (of malt)	
Malt bagasse	
Washing water	
Remains of hops	
Trub	
Yeast	
Water	
Glass	
Metal cover	
Cardboard	

III. Which of the above wastes does the company consider the most important to be treated? List three in order of importance (where the first is considered the most important to the company).

IV. Do you know any other reuse destination that can be given to the waste listed below? If so, could you describe which ones?

Type of residue	Possible and alternative destination for the waste generated
Malt bark	
Starch (grinding powder)	
Sacks and bags (of malt))	
Malt bagasse	
Washing water	
Remains of hops	
Trub	
Yeast	
Water	
Glass	
Metal cover	
Cardboard	

V. Does the company consider the issue of reuse of waste to be important? If yes, why?

VI. Would you consider implementing a generic model in the company for waste management and reuse of BSGs?

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