Travail de fin d'études: "Exploring the supply chain for brewery¿s by-product recycling: A study on a potential alternative for a brewery¿s by-product valorization"

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Diplôme : Master : bioingénieur en chimie et bioindustries, à finalité
Année académique : 2022-2023
URI/URL : http://hdl.handle.net/2268.2/17802

European Master in Biological and Chemical Engineering for a Sustainable Bioeconomy

Master thesis report

submitted to obtain the degrees of

Master in Biology AgroSciences (BAS) of the University of Reims Champagne-Ardenne

Master in Integrative Biology and Physiology (BIP) of the University Paris-Saclay, operated by AgroParisTech

Master in Bioengineering: Chemistry and Bioindustries of the University of Liège

Exploring the supply chain for brewery's by-product recycling: A study on a potential alternative for a brewery's by-product valorization

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Confidentiality: Yes X No ☐ Privacy expiration date: 01/08/2033

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Masters Dissertation

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Acknowledgements

I would like to express my gratitude to all those who have contributed to the successful completion of this work. Their unwavering support, invaluable guidance, and constant encouragement have played a significant role in shaping my academic journey.

Firstly, I would like to extend my sincere appreciation to Anteja, the company for which I conducted my thesis research. I am immensely grateful for the opportunity to work with such a dynamic and forward-thinking organization. My deepest gratitude goes to my supervisor and the entire team at Anteja for their invaluable support, mentorship, cooperation, and provision of necessary resources throughout my research. Their expertise, insights, and willingness to share their knowledge have been instrumental in the development of my thesis. Furthermore, I would also like to express my gratitude to the Slovenian company that participated in the project and provided valuable information, contributing to the overall success of this research.

Secondly, I am indebted to my academic professors and the BIOCEB coordinators, whose guidance and expertise have been indispensable throughout my two-year journey. Their unwavering commitment to imparting knowledge, challenging my intellectual boundaries, and nurturing my growth have been pivotal in shaping the outcome not only of this thesis but of the person who I am today.

In addition, I would like to express my gratitude to my friends and family, both those I have known prior to undertaking this master's degree and those I have had the pleasure of meeting during the course of my studies. Their unwavering support, understanding, and encouragement have been one pillar of strength throughout this academic endeavor. What I have learnt from them, their belief in my abilities and their constant motivation have been a source of inspiration and have propelled me forward in times of doubt. I will always be profoundly grateful for their presence in my life.

Abstract

The current global challenge of climate change has led to increased attention on sustainable development practices. In response, the circular economy has emerged as an alternative to the linear economy model, seeking to combat waste, CO_2 emissions, and resource depletion. In this context, the primary objective of this work was to identify and evaluate various circular alternatives for the valorization of a by-product generated by a Slovenian brewery. The analysis explored different biomass valorization alternatives as a potential path to address the major problem of ever-increasing organic waste production through the promotion of circular economy principles.

In addition to the aforementioned analysis, the study also assessed the feasibility of implementing a Black Soldier Fly (BSF) system as an alternative to by-product management. This innovative approach involves the use of brewers' spent grains (BSG) as feed for insect farming, specifically for BSF larvae. The evaluation examined an integral set of criteria including technical, climate change mitigation potential and market assessments for this by-product management strategy within a circular economy framework.

The selected approach involved extensive research and data collection, including literature review, interviews with key stakeholders, and a review of existing documentation of the company.

This study aims to contribute to the body of knowledge on circular economy and by-product management practices within the brewing industry. By exploring different valorization options, the study advances our understanding of how breweries can effectively manage their by-products and move towards a more sustainable and resource-efficient brewing process. The results of this study provide valuable insights and practical recommendations for breweries to enhance their operations while keeping waste generation and environmental impact to a minimum.

Introduction

It is projected that the global population, which is currently 7 billion, will likely grow to a range of 8 to 10 billion by the year 2050 (Lutz and Kc 2010). Is important to note that, as the population continues to grow, the demand for natural resources is increasing at an unprecedented rate (Panel 2011). This will lead to a range of environmental challenges, including deforestation, water scarcity, and climate change (Warner et al. 2010). To meet the needs of a growing population while protecting the environment, the adoption of sustainable practices and technologies is essential. This includes: Minimizing waste, reducing greenhouse gas emissions and promoting resource efficiency. By adopting these measures, we can effectively address the challenges of climate change and population growth while ensuring greater efficiency and sustainability for a sustainable future.

In this sense, new business models that incorporate circular economy approaches are a promising response to these challenges. These models focus on sharing, reuse, repair and recycling to create circular value chains and closed-loop systems. In this context, the utilization of by-products for the production of value-added products or valuable applications is closely linked to the concepts of circular economy and zero-waste manufacturing processes (Visco et al. 2022).

The model offers a range of benefits such as reduced environmental impact, increased resource efficiency, and new economic opportunities (Camilleri 2018). In fact, it has gained attention from policymakers, businesses, and academia as a means of promoting sustainable development. For example, there have been efforts from the European Commission to implement strategies to "close the loop" in industrial production systems from a circular economy approach. These efforts aim to transform the EU economy into a more sustainable, low-carbon emissions, and resource-efficient system (González-García, Morales, and Gullón 2018).

However, there are still challenges that need to be overcome, such as shifting the traditional linear economic mindset and developing new technologies and business models and value chains that support the circular economy. Thus, promoting sustainability in a technical and economically feasible way.

State of the art

The circular economy

Definition

The circular economy is a system that seeks to maximize the value of products, materials, and resources within the economy while minimizing waste generation (Korhonen, Honkasalo, and Seppälä 2018). The primary objective of this system is to create closed loops of material flows rather than the traditional linear scheme which has been reported as unsustainable (Korhonen et al. 2018).

Although the idea of a circular economy is not new – actually, the term was formally used first in 1990 by Pearce & Turner (McGregor 1991) - , it has recently gained popularity due to various benefits:

- **Mitigate resource shortage:** Circular economy is designed to keep materials and products in use for as long as possible, which can help to mitigate resource shortages. The circular economy achieves this by reducing the demand for new resources and maximizing the use of existing resources. For example, materials that would have been discarded as waste in a linear economy can be reused, repaired, or recycled in a circular economy. This reduces the need for new resources to be extracted, processed, and transported (Shen, Li, and Wang 2020).
- **Reduce environmental pollution:** By promoting the principles of designing out waste and pollution, keeping products and materials in use, and regenerating natural systems, circular economy reduces environmental pollution. This is achieved through various practices, such as: reducing the use of virgin materials and implementing closed-loop production systems that minimize waste (Dey et al. 2022). In addition, circular economy encourages the use of renewable energy sources and the reduction of greenhouse gas emissions, which can also contribute to the mitigation of climate change (Yang et al. 2023).
- **Increase system efficiency and promote waste reduction:** Focuses on minimizing waste throughout the product life cycle. Thus, circular economy strategies can help to reduce waste and improve the overall sustainability of

industrial production processes by utilizing waste as a raw material (Yang et al. 2023).

Circular economy perspectives

As commented before, the concept of circular economy has gained widespread recognition and support across the globe. In fact, several national governments such as China, Japan, United Kingdom, France, Canada, Netherlands, Sweden and Finland, have been promoting its implementation in different businesses as a mean of achieving sustainable environmental and economic development (Korhonen et al. 2018).

From an economic point of view, the adoption of circular economy principles can bring significant economic benefits. For example, the global economy could benefit up to 1000 billion US dollars annually through circular economy initiatives while the European Commission estimates that the European manufacturing sector just by itself can generate annual figures of 600 billion euros of economic gain (Korhonen et al. 2018). These potential economic benefits include job creation: a study in 2017 estimates that improving the EU's resource productivity with circular economy practices by 2% could help create up to two million additional jobs in 2030 (Cambridge 2017).

Circular economy growth expectations for funding are also positive. Nowadays, investments in the circular economy represent a small fraction in comparison with linear investments, accounting for only 10%. Nevertheless, there is a significant potential for the circular economy: reports highlight that around €320 billion of additional investment might be available by 2025 (Ellen MacArthur Foundation and SYSTEMIQ 2017).

The circular economy has also been examined from an environmental perspective. In this sense, studies have shown that it can have a significant impact on reducing greenhouse gas (GHG) emissions. For instance, a study conducted in 2014 estimated that resource efficiency improvements could lead to a reduction of 2 to 4% of GHG emissions annually (Cambridge 2014). Another study projected that the implementation of circular economy practices aimed at reducing food waste and reusing by-products could avoid between 56.5 Mt to 96.5 Mt of GHG emissions by

2025 (European Environmental Bureau 2014), with a general expected reduction of GHG of 48% in 2030 and 83% by 2050 (Behrens 2016). These findings demonstrate the potential for the circular economy not only to avoid GHG emissions but also to reduce them.

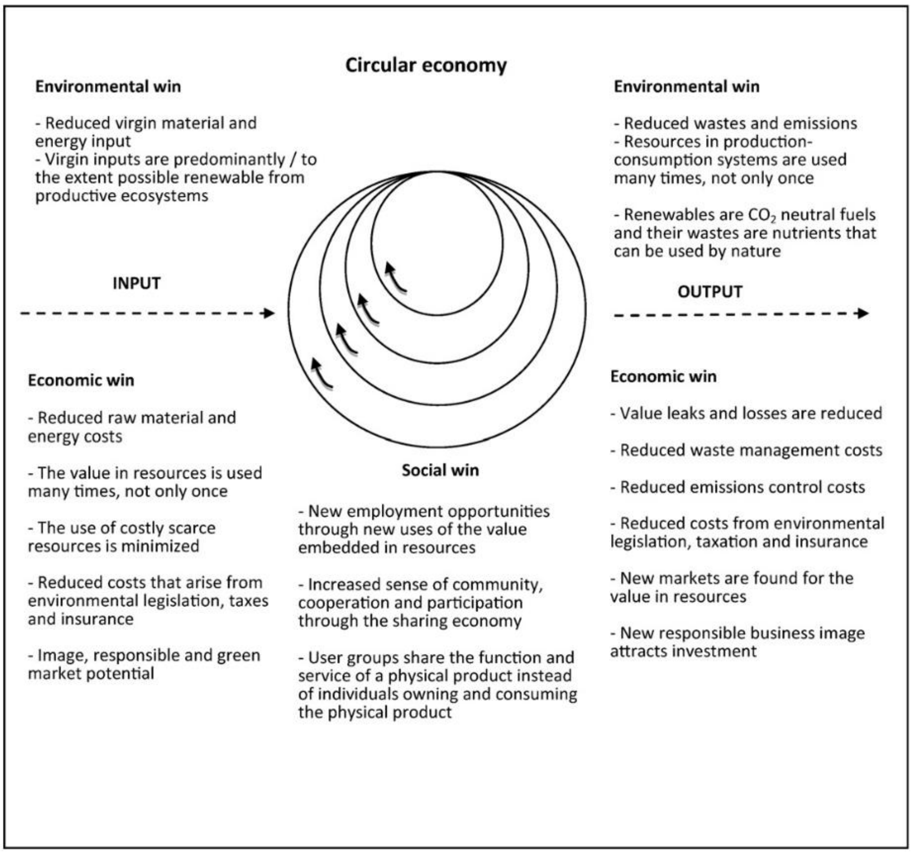
How the combination of circular economy and industry can contribute towards achieving more sustainable scenarios

The integration of sustainable strategies into industrial practices has been widely recognized as a critical factor for achieving impactful sustainable performance (Dantas et al. 2021). Innovative approaches, such as the circular economy, have been identified as key enablers for translating the valorization of by-products into practical implementation. Therefore, exploring and developing common ground between industry and sustainability practices has become increasingly important, attracting attention from both the academic and industrial communities.

For example, a comprehensive approach to valorizing by-products generated at different stages of industrial processes was proposed by Gullón in the context of olive oil production (Gullón et al. 2020). The proposed biorefinery system, which incorporates circular economy principles, has the potential to generate economic and environmental benefits simultaneously. Similarly, Thoppil and Zein explored the potential of producing biodiesel from spent coffee grounds and found that sustainability implementations brought remarkable benefits, such as reducing dependence on fossil fuels and contributing to a more sustainable industrial system (Thoppil and Zein 2021). Another study focused on a paper-manufacturing organization and explored sustainable opportunities within cutting-edge processes and circular approaches. The study highlighted the benefits of integrating sustainable practices and industrial processes, such as reduced waste production, reuse of by-products, and increased efficiency, contributing to cost savings (Bhardwaj et al. 2019). These examples illustrate how incorporating circular strategies into industrial processes can generate both economic and environmental benefits, promoting a more sustainable and efficient industrial system.

As stated, the implementation of circular economy approaches in industrial processes has emerged as a promising pathway towards achieving sustainable development goals. But, in order to promote circular economy practices in the industrial sector, it is crucial to facilitate their adoption by companies. One of the key challenges faced by companies is the integration of new technologies in a feasible manner. To overcome this challenge, it is important to provide companies with access to knowledge, resources, and feasibility analysis. Companies need to be aware of the various available options in order to understand their advantages and disadvantages, and assess the feasibility of their implementation considering legal, technical, and market aspects. This support can play a crucial role in promoting the adoption of circular economy practices, thereby contributing to economic and environmental progress for society. **Figure 1** illustrates the comprehensive nature of these practices and highlights their associated benefits.

Figure 1: Circular Economy as a pathway for achieving economic, environmental, and social sustainability (Korhonen et al. 2018)



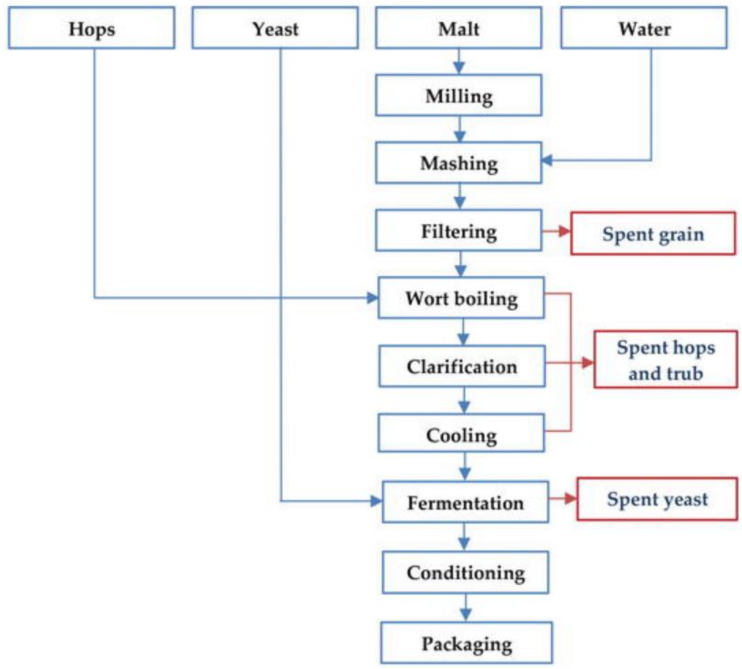
Study Case

In today's world, around 38 billion metric tons of organic waste are produced annually (S et al. 2016). This high amount of production and its continuous rise are considered a growing concern as it poses several problems. Firstly, if not properly managed, organic waste can threat the quality of the environment by contaminating water, air, soil and by leading to the emission of greenhouse gases (B. Pastor et al. 2015). Secondly, it also raises important concerns from a health point of view as it has been associated with pathogens and disease spread (Shahida Anusha Siddiqui et al. 2022). Up to now, the main ways for treating these organic wastes have been landfilling, composting, or incineration (Kim et al. 2021); activities that have been severely criticized due to their detrimental consequences. It is also important to note that the widespread linear production model of "take, make, and dispose" has significantly contributed to this alarming waste generation (Jørgensen and Pedersen 2018). Therefore, finding efficient ways to manage organic waste is crucial for environmental sustainability.

The brewery industry

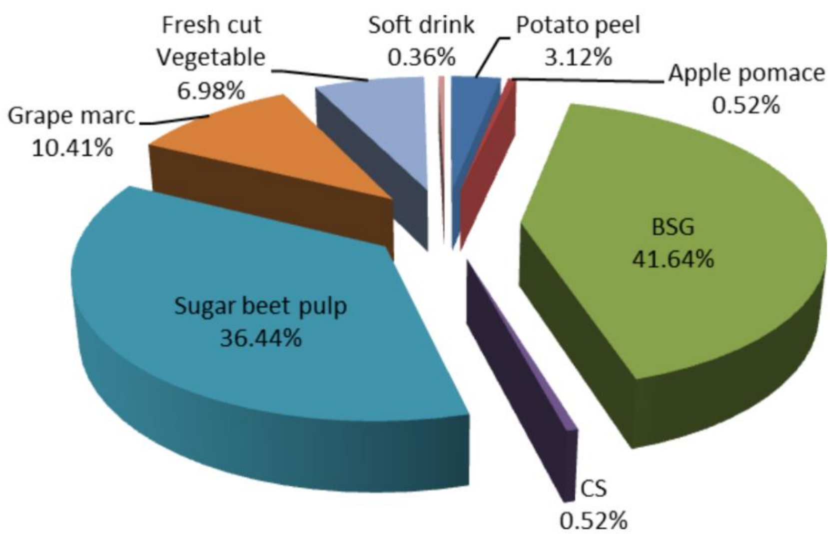
Among the food and drink industry, the brewing industry is one of the largest sectors. As the fifth most consumed beverage in the world, beer is a highly popular beverage characterized by an average consumption rate of 9.6 liters per capita among individuals aged 15 and above (Olajire 2020). The brewing industry produces more than 1.94 billion hectoliters of beer per year (Olajire 2020), and more than 401 million of those hectoliters are produced by countries of the European Union (Assandri et al. 2021). This significant production also leads to the generation of great amounts of brewery processing by-products which mainly consist on used grain, yeast, and leftover hops or hot trub (Kerby and Vriesekoop 2017). For example, the three largest beer-producing countries in the world - China, the USA, and Brazil - generate roughly 16.9 million tons of spent grain, 250 thousand tons of hot run, and 2.1 million tons of residual yeast per year. (Thiago, Pedro, and Servulo 2014). **Figure 2** depicts the main parts of the brewing process from where these wastes are generated.

Figure 2: Illustration of by-product generation points in the brewing process (Fărcaş et al. 2017).



The spent barley grain, which is known as BSG, is the main by-product of the brewing process accounting up for 85% of the total by-products generated; it is also the largest contributor within the agro-food wastes **(Figure 3)**. The estimated global annual production of BSG is roughly between 38 to 39 million tons, with 3.4 million tons of BSG being produced in the European Union alone (Assandri et al. 2021). Due to this high by-product generation and the negative environmental consequences they entail, the valorization of this brewery by-product is a significant challenge for the brewing industry.

Figure 3: *Relative contribution of each agro-food waste in Europe (Procentese et al. 2019)*



Currently, the majority of brewery by-products are either disposed of in landfills or incinerated, leading to environmental pollution and economic losses for breweries (Visco et al. 2022). Therefore, the increasing interest on finding ways in which these brewery by-products can be used for other applications while minimizing environmental impact and ensuring industrial and economic viability. In this sense, the integral evaluation of potential circular practices play a key role for the addressing this challenge through sustainable development initiatives (Ngan et al. 2019).

Brewers' spent grains as a source for value-added applications

Composition

In the beer brewing process, one of the initial operations is called mashing. During this step, the cereal grains are rendered soluble for wort extraction. Once the extraction is completed, a residual by-product is generated: brewers' spent grains (BSG) (Fillaudeau, Blanpain-Avet, and Daufin 2006).This insoluble solid fraction of the grains used for the beer production, is known to be a significant source of high nutritional compounds (Mitri et al. 2022). In general, BSG grains are mainly composed of lignocellulosic fibers made of hemicellulose (28.35%), cellulose (16.25%) and lignin (7.27%), which comprise around 70% of BSG's dry weight, and protein that constitutes approximately 20% of the material on a dry basis (Cooray and Chen 2018). In addition, other compounds including monosaccharides, lipids, oligosaccharides, polysaccharides, amino acids, vitamins, minerals, and phenolic compounds are found in BSG as well **(Table 1).** Nevertheless, it is worth noting that this chemical composition may vary depending on various factors such as the type of barley grains used, beer recipe, the time of harvesting, and the brewing process (Vriesekoop et al. 2021).

Table 1: BSG composition (Mitri et al. 2022)

Components	Most common molecules
Lipids	Triglycerides, Free Fatty Acids
Proteins	Hordeins, Glutelins, Globulins, Albumins
Amino Acids	Phenylalanine, Lysine, Tryptophan, Histidine, Methionine (Essential); Alanine, Glycine, Proline, Serine (Non-essential)

Vitamins	Biotin, Choline, Pantothenic acid, Folic acid, Niacin, Riboflavin, Thiamine, Pyridoxine
Minerals	Phosphorus, Calcium, Cobalt, Potassium, Copper, Iron, Magnesium, Manganese, Selenium, Sulphur, Sodium
Phenolic Compounds	Ferulic acid, p-coumaric acid

Besides these components, BSG has a high moisture content of approximately 80%. This combination makes it highly susceptible to microbial contamination, resulting in a short lifespan of only 7 to 10 days (Mitri et al. 2022). Due to these properties and its composition, brewer's spent grains can be used as an affordable and highly nutritional source for a variety of applications.

Current main management practices for Brewers' Spent Grains

In general, brewer's spent grains are currently used for the production of low value composts, disposed of in landfills or sold as livestock feed (Olajire 2020). Approximately 70% of BSG in Europe is utilized for animal feed while landfilling, accounts for around 20% of the total management strategies for BSG and 10% is distributed in other applications (Visco et al. 2022).

Animal feed additive

Brewer's Spent Grain has been used as a feed additive for various animals, including cattle, pigs, fish, and poultry. Research studies have demonstrated the potential of BSG feed ingredient (Jackowski et al. 2020). However, when utilized for animal feed, it is usually considered as a low-value product with a market price of only 1 and 20 euros per ton (Fărcaş 2014).

It is crucial to highlight that BSG should not be used as a complete independent feed for animals. BSG's composition characteristics, such as its low fat and carbohydrate content, make it necessary to combine with other feed sources, particularly cereals and protein-rich legumes. This is to ensure a balanced and nutritious diet for the animals. When not done, studies, like the one conducted by Faccenda et al., have reported problems like diarrhea and decreased fertility in cows when fed exclusively with BSG (Faccenda et al. 2017).

Landfilling

Due to its substantial environmental disadvantages, landfilling is frequently regarded as the least preferred choice in the waste management hierarchy (Zupančič et al. 2022). When BSG are disposed of in landfills, they undergo anaerobic decomposition, leading to the emission of environmentally hazardous gases such as methane (CH4), carbon dioxide (CO2), and non-methane volatile organic compounds (Khademi et al. 2022). In fact, every ton of BSG landfilled release approximately 513 kg of CO_2 equivalent greenhouse gases (Visco et al. 2022).

In addition to greenhouse gas emissions that contribute to the ozone atmosphere depletion, landfilling also has other impacts that can have harmful effects on ecosystems and aquatic life such as acidification, eutrophication and ecotoxicity (Zupančič et al. 2022).

Composting

This method, considered as a form of low value material recovery, involves blending brewer's spent grains with other organic waste streams. Through the addition of micro-organisms, these blended materials undergo bio-oxidation and humification processes, ultimately transforming into compost (Waqas et al. 2023). This approach is preferred over landfilling because the resulting compost can also serve as a valuable fertilizer (Finnveden et al. 2005). However, it is important to note that this method also possess some drawbacks. The composting process of BSG and organic waste generates GHG, including carbon dioxide (Sánchez et al. 2015).

Other applications

While brewers' spent grains are commonly utilized in the aforementioned practices, there have been other methods developed for its valorization. For example, BSG has shown great potential as a material for producing activated carbon, which has a wide range of applications including decolorizing, solvent recovery, water treatment, deodorizing, gas purification, precious metals recovery, and catalysis (Badr et al. 2000). BSG has also been studied for its potential in biomethane production (Jackowski et al. 2020). Furthermore, BSG is a valuable source for extracting high-value compounds such as arabinoxylans, proteins, polyphenols, antioxidants, and glucose (Du et al. 2020; Spinelli et al. 2016; Tang et al. 2009). It has even been evaluated for its use in construction materials as fillers and reinforcement materials as well (Jackowski et al. 2020).

Limitations for BSG utilization

In recent times, there has been a significant trend towards exploring the potential of agro-food byproducts, such as brewer's spent grain, for various applications. These studies generally aim to transform these previously regarded as waste materials into valuable resources (Guido and Moreira 2017). This approach arises from the pressing need of addressing the environmental challenges our world is currently facing. Finding alternative uses for byproducts rather than using the traditional disposal practices can contribute positively in this regard. However, the task of effectively implementing these strategies is highly complex, as it depends on a multitude of interconnected factors (Pan et al. 2015).

Location plays a crucial role in determining the feasibility of BSG valorization (Aliyu and Bala 2011). The specific composition and availability of this material can vary across different regions and industries, influencing their suitability for particular applications. Additionally, the industrial effectiveness of converting these byproducts into valuable products needs to be considered. Technical deployment, including the development of efficient and scalable processes, is essential for successful and impactful implementation as well (Rissman et al. 2020).

Furthermore, societal factors such as social acceptability and market adaptation play a significant role in determining the viability of these initiatives (Aliyu and Bala 2011). Market demand and the development of appropriate supply chains are critical for creating a sustainable market ecosystem as well.

On the other hand, economic feasibility is also a crucial factor that must be addressed to ensure the long-term viability of these circular economy strategies (Lewandowski 2016). Cost-effective processes and accessible business models are essential for fostering the growth of sustainable practices centered around byproducts valorization.

Despite extensive laboratory-based research, the transition of these technologies from the experimental stage to industrial-scale projects has encountered numerous challenges. The integration of scientific developments, encompassing all the key challenges mentioned above, represents a promising pathway towards realizing a more sustainable, environmentally friendly, and circular world.

It is important to recognize that the true potential impact of these technologies will only be fully realized once they are successfully scaled up and implemented in today's businesses. Therefore, comprehensive and holistic approaches that address all the relevant factors are necessary to bridge the gap between scientific advancements and real-world implementation. This comprehensive integration of scientific, technological, economic, legislative and social aspects is crucial for advancing towards a more sustainable future.

Significance of circular value chain business modeling for brewery by-products valorization

The significance of developing circular value chains for the real valorization of brewery by-products on an industrial scale cannot be overstated. There are five business models outlined in the OECD report on circular economy provide different ways to achieve resource efficiency and circularity in the economy (OECD 2019):

- Circular supply model: replacing material inputs with bio-based, renewable, or recovered materials.
- Resource recovery model: recycling waste into secondary raw materials.
- Product life extension model: extending the period of existing products.
- Sharing model and product service system model: sharing of under-utilized products to reduce demand for new products.
- Product service system model: marketing services instead of products to improve incentives for green product design.

While these models are not completely new, the circular economy approach emphasizes their integration and scaling to achieve systemic change (Geissdoerfer et al. 2017). They are key components of the circular economy as it creates new opportunities for economic growth and environmental sustainability (Maio and Rem 2015). Therefore, the importance of adopting circular supply models in processes; as such can help with upcycling, which is the process of transforming waste into high-value materials (Roy et al. 2021). This process involves using innovative technologies and design supply chains to create products of value.

In light of these considerations, exploring and implementing circular value chains within real businesses becomes crucial for realizing the full potential of brewery by-products valorization. Such an approach can lead to substantial positive impacts, not only in terms of environmental footprint reduction but also in terms of economic viability. By embracing circularity in their operations, industries can unlock new avenues for resource optimization, and the creation of more sustainable products (Bonato et al. 2022).

Methodology

Research protocol

In the interest of contributing to the efforts towards climate change mitigation, this study consisted on the identification of potential by-product management solutions for the brewery industry. This involved a literature review for BSG valorization alternatives, followed by the development of the specific case study that focuses on analyzing the real scenario of the brewery producer in Slovenia. The methodology used for the development of this work was structured into 3 main stages: (a) literature review for BSG valorization solutions identification, (b) assessment of the advantages and disadvantages of each particular solution, (c) selection and feasibility analysis of the potential valorization solution identified in the previous two stages.

Firstly, a thorough and comprehensive review of recent and contemporary literature on management strategies for brewery spent grain was done. The research involved consulting a wide range of primary data sources, including books, articles published in reputable journals, and periodicals. The aim was to gather insights from recognized strategies that consist of the adoption of sustainable practices for BSG valorization. By this analysis, an understanding of the various approaches employed for BSG management was gained.

Based on the results from the first literature review, a comprehensive assessment that specifically focused on the unique characteristics of each BSG management technology was made. The primary objective of this assessment was to identify and analyze the advantages and disadvantages associated with each practice, allowing for a meaningful comparison of the different strategies. Thus, enabling an evaluation of the feasibility and effectiveness of each approach in relation to the brewery's value chain of study.

Main scope and objectives

The main objective of this study was to identify and assess the viability of a by-product management option for a brewery plant in Slovenia. BSF was selected as the preferred solution to be subjected to further study after thorough analysis of brewery by-product treatment options.

The general objectives of this study were to determine the technical, legislative, environmental and market viability of the utilization of brewery waste for feed production in Slovenia.

In order to efficiently frame the research, the following specific objectives of the study were proposed:

1. To determine the technical feasibility of utilizing BSG for an insect feeding application.
2. To describe the current waste management system employed by the brewery in Slovenia for the spent barley grain in order to characterize its structure, the waste streams and its treatment and disposal methods.
3. To analyze the potential environmental benefits of the alternative waste management proposal.

Research questions

Specific research questions where posed in order to accomplish the aforementioned objectives as follows:

- What is the cost involved in obtaining the raw material used for beer production for the current application?

Refers to the cost of obtaining the BSG grains for the current off taker.

- What is the location where the raw material is sourced from and to where is it send to?

This information can be significant, as it affects directly the CO_2 emissions associated with the transportation of by-product.

- What is the composition of the brewers' spent grains generated?

The chemical composition of the grains is essential for identifying potential applications.

- What are the current theoretical applications for this feedstock?

Refers to the opportunities identified for the utilization of BSG based on research and scientific knowledge

- What is its market viability?

This information is essential for assessing the most feasible, environmental and economically viable by-product valorization option.

Data collection

Data was gathered from multiple sources. The first stage of the study, focused on performing a thorough review of the specific literature pertaining to the main recycling alternatives for brewery spent grains. This involved consulting articles published in reputable journals, which served as the primary data sources. The literature review encompassed a wide range of topics, including but not limited to, the utilization of BSG in animal feed production, bioenergy generation, human nutrition, and its applications for the extraction of high value compounds.

Following an in-depth analysis, 31 studies that were deemed highly relevant and provided substantial insights into the topic, were selected. These studies served as the foundation for further examination and analysis in the subsequent stage of the study. This second stage, the assessment of technologies, aimed to understand the specific characteristics of the technologies based on their properties.

Table 2: Research protocol

Research Protocol	Description
Publications	Books, journals, and conference papers
Language	English
Data range	2000-2022
Search fields	Titles, abstracts and keywords
Main search term	Brewery spent grain
Criteria for inclusion	Studies presenting valorization alternatives for BSG
Criteria for exclusion	Studies that did not present specific technologies for BSG but for other brewery by-products
Data extraction	Reading of publications
Data analysis	Analysis of information available on the publications

To complement the results and validate the more appropriate technology, the last stage was made. For this, the information about the specific characteristic of the Slovenian Brewery provided by the company, along with direct conversations with the brewery responsible was gathered. Having collected these data and understanding the specific situation for the study in case, a valorization solution was selected and its feasibility evaluated.

Results and discussion

The results of this study are divided into two different sections. The first one evaluates ways to utilize the by-product of interest. It presents advantages and disadvantages of the technologies, as its analysis can provide valuable insights into the most suitable by-product management option. The second section presents the chosen alternative, provides additional information about it and presents relevant feasibility aspects.

Slovenian Brewery characteristics and company profile

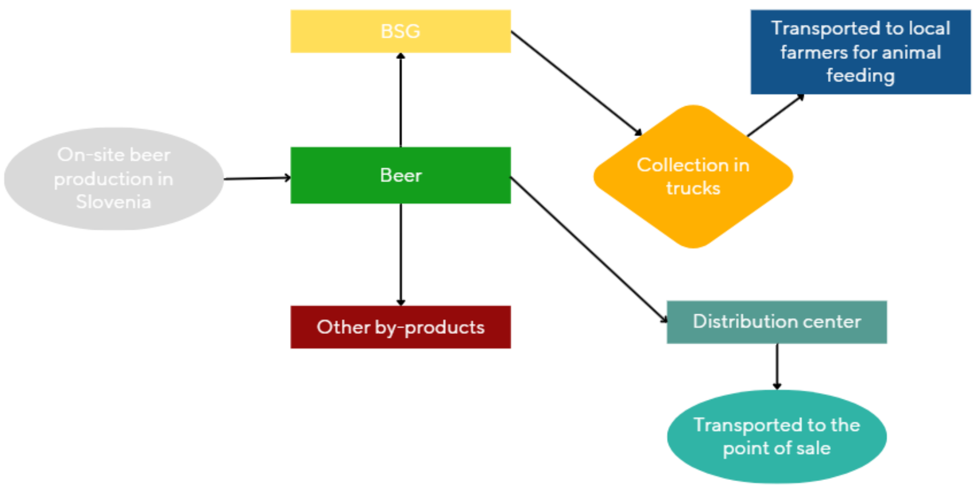
The Slovenian Brewery, subject of this study, demonstrates a strong commitment to enhancing sustainability and continuously improving its environmental impact through its operational practices. A key objective of the brewery is to achieve complete emissions reduction across its entire value chain by 2040. Furthermore, they are actively exploring strategies to attain net zero emissions in scope 1 and 2 by 2030, while simultaneously targeting zero waste to landfill by 2025. This proactive approach underscores the brewery's dedication to environmental stewardship and underscores their efforts to mitigate the ecological footprint associated with their operations.

In a global context, the brewery under examination generates an estimated average of 3.0753 million tons of brewers' spent grains per year. This production is derived from their total global beer production of 180.9 million hectoliters, with an average quantity of 17 kg of BSG produced per hectoliter.

As a reputable and dependable supplier of BSG, the brewery serves two customer segments: local farmers, who receive direct supply, and intermediaries, who acquire the BSG through indirect channels. The price of BSG varies between 0 and 56 euros per ton, reflecting significant regional disparities in the benefits obtained from its sale.

According to the specific analysis of the brewery value chain in Slovenia, approximately 40,000 tons of brewers' spent grains are currently being produced. These by-products are entirely used for animal feed mainly in dairy and beef farms. The management of these by-products is handled by a company that connects with local farmers in Slovenia, negotiating an average price of 30 euros per ton. Logistics-wise, the grains are typically transported to the farmers' silos using trucks. The choice of truck trailer depends on the volume to be transported, which varies based on production rates and seasons. **Figure 4** shows the value chain described.

Figure 4: Schematic representation of the current value chain of the brewery



In this sense, including circular practices in their operations represents a viable pathway for minimizing waste and maximizing the efficient utilization of by-products, thus facilitating a substantial reduction in their environmental footprint and contributing to the realization of their ambitious objectives.

Assessment of possible technologies and strategies for valorization of BSG

As explained in the previous sections, the principle of circular economy can help to change production models by upcycling its different by-products (Boons et al. 2013). By utilizing these by-products, breweries can reduce their environmental impact and improve their sustainability (Narisetty et al. 2021). Additionally, these alternative uses can provide economic benefits, such as the creation of new revenue streams.

One of the aims of this study was to assess various ways in which brewer's spent grain can be utilized. For this purpose, firstly main models for BSG recycling and reuse that include animal feed, human food, composting, biogas, substrate for mushrooms production, substrate for enzymes production, absorbents, bulding materials such as concrete and ceramic, paper, bricks bioethanol production, xylitol, replacement of wood, and antioxidant were identified **(Table 3).**

Table 3: Identification of different alternatives for reuse and valorization of BSG

Reference	Animal feed	Biofuel	High-Value Compounds	Substrate for mushrooms production	Bioethanol	Human food	Substrate for enzymes production	Absorbents	Building materials	Cosmetics
(Plaza et al. 2017)		*								
(Gupta, Jaiswal, and Abu-Ghannam 2013)			*							
(Wang, Sakoda, and Suzuki 2001)				*						
(Kopsahelis et al. 2007)					*					
(Steinmacher et al. 2012)						*				
(Kaur and Saxena 2004)	*									
(Kafle and Kim 2013)		*								
(Niemi et al. 2013)	*					*				
(Faulds et al. 2009)			*							
(Tang et al. 2009)			*							
(Mussatto et al. 2008)			*							
(Treimo et al. 2008)							*			
(Low, Lee, and Liew 2000)								*		
(Plessas et al. 2007)						*				
(Hashemi et al. 2011)							*			
(Gregori et al. 2008)							*			
(Wang et al. 2001)							*			
(Oluseyi et al. 2011)						*				
(Stojceska and Ainsworth 2008)						*				
(Russ, Mörtel, and Meyer-Pittroff 2005)									*	
(Lu and Gibb 2008)								*		
(Almeida et al. 2003)										
(Novik et al. 2007)							*			
(Xiros and Christakopoulos 2009)					*		*			
(Xiros et al. 2008)			*							*
(Almendinger, Rohn, and Pleissner 2020)										
(Barbu et al. 2021)									*	
(Codina-Torrella, Rodero, and Almajano 2021)			*							
(Ivanova et al. 2017)			*							
(Ktenioudaki et al. 2012)						*				
(Chia et al. 2020)	*									

Afterwards, and through a desk-based literature review, each alternative was evaluated individually based on their advantages and disadvantages. It is important to note that selecting the optimal by-product management option requires a thorough analysis of the specific circumstances, processes, and facilities of each particular case, as the quantity and type of by-products generated, the brewery's location and size, and available infrastructure can all contribute to make one alternative more suitable than other (Mussatto 2014). Thus, to determine the most suitable BSG management strategy for the Slovenian brewery, a comparative assessment of the various options identified was conducted. The results of this comparative assessment of BSG's management strategies are shown in **Table 4.**

Table 4: Comparative assessment of BSG's management strategies

Valorization alternative description	Advantages	Disadvantages	Reference
Using brewer's spent grain (BSG) as a feedstock for butanol production through ABE fermentation	-BSG has a high carbohydrate content, making it a promising feedstock for butanol production The ABE fermentation process using C. beijerinckii DSM 6422 is a well-established process for butanol production.	-Optimization is needed to remove inhibitors. -The overall process has not been scaled up.	(Plaza et al. 2017)
Effects of chemical compositions and ensiling on the biogas productivity and degradation rates of agricultural and food processing by-products	-Provides a renewable alternative to fossil fuels by using BSG for energy production.	-Efficiency of biogas production can be affected by various factors such as the type and quality of the feedstock, the operating conditions, and the presence of inhibitors. -Initial investment cost for setting up a biogas plant can be high -The process requires skilled personnel for operation and maintenance.	(Kafle and Kim 2013)

Utilization of brewers' spent grain (BSG) for the development of a fermented liquid product rich in value-added phenolic compounds	-Generation of rich value-added phenolic compounds, which have antioxidant properties.	-Study was conducted in a laboratory setting. -Further research is needed to determine the feasibility of scaling up the process for commercial production.	(Gupta, Jaiswal, and Abu-Ghannam 2013)
Using spent beer grains as an alternative substrate material for mushroom cultivation	-Applicable in a commercial scale.	-Very sensitive technology to the type of spent grain and moisture content.	(Wang, Sakoda, and Suzuki 2001)
Yeast supports for alcoholic fermentation of molasses	-High fermentation rates.	-The study only evaluated the quality of the produced ethanol -The paper does not provide information on the feasibility of scaling up the technology for industrial applications.	(Kopsahelis et al. 2007)
Effects of medium supplementation and pH control on lactic acid production from brewer's spent grain	-The combination of a commercial cellulase preparation and Lactobacillus delbrueckii allows for efficient conversion of BSG into lactic acid.	-High process complexity and high operational costs.	(Mussatto et al. 2008)
Incorporation of brewery waste in supplementary feed and its impact on growth in some carps	-The use of BSG in supplementary feed for catla, rohu, and mrigal fishes showed better growth performance in terms of body weight gain, especially when the feed contained 30% BSG, giving a potential nutritional advantage.	-Use of brewery waste in fish feed may not be suitable for all fish species.	(Kaur and Saxena 2004)

Bioconversion of brewer's spent grains by reactive extrusion and their application in bread-making	-Innovative pplication. -Bread prepared with untreated spent grains together with the enzymes directly added to the dough had larger specific volume and was soft. -No difference in sensorial tests, meaning a potential use in a real market scenario.	-There is no information regarding large scale applicability of the technology.	(Steinmacher et al. 2012)
Protease-induced solubilization of carbohydrates from brewers' spent grain	-The technology allows the recovery of over 50% of the protein content present in BSG. This protein can be further utilized in various value-added applications, such as animal feed, bioplastics, or as a nutrient source in microbial fermentation processes. -This compound has potential applications in various industries, such as food, pharmaceuticals, and cosmetics.	-The hydrolysis process using the microbial proteases takes 24 hours. This relatively long duration may pose challenges in scaling up the technology to an industrial scale, where time efficiency is crucial. -The technology involves the use of microbial proteases, which may require specialized production and purification processes. This complexity could increase the cost and technical requirements for implementing the technology on an industrial scale.	(Faulds et al. 2009)
Recovery of protein from brewer's spent grain by ultrafiltration	-The use of ultrafiltration allows efficient recovery of protein. -Ultrafiltration technology is well-suited for industrial-scale operations. It can be implemented in large-scale processing facilities, making it feasible for commercial	-The implementation of ultrafiltration technology requires specialized equipment and infrastructure. -Initial investment costs and operational expenses associated with maintenance, energy consumption, and membrane replacement can be significant.	(Tang et al. 2009)

	production and valorization of BSG protein.		
Pre-hydrolysis with carbohydrases facilitates the release of protein from brewer's spent grain	-The protein component in BSG has potential to be used as a source of human and animal dietary protein, if it can be extracted without too much deterioration in its techno-functional properties.	-Efficiency of the process may depend on various factors such as the type and concentration of carbohydrases used, the pH, temperature of the reaction, and the duration of the treatment. -The techno-functional properties of the extracted protein may be affected by the pre-hydrolysis process, which could limit its potential applications.	(Niemi et al. 2013)
Immobilization of kefir and Lactobacillus casei on brewery spent grains for use in sourdough wheat bread making	-Breads produced with BSG, particularly with this method, exhibit lower rates of water evaporation and staling.	-The use of biocatalysts and sourdough fermentation introduces additional complexity to the bread production process. -Increased production costs. -BSG-derived bread may have a distinct flavor and texture compared to traditional bread.	(Plessas et al. 2007)
The potential of brewer's spent grain to improve the production of α-amylase by Bacillus sp. KR-8104 in submerged fermentation system	-The use of BSG reduces the need for expensive raw materials in the synthetic media, such as soluble starch, meat extract, yeast extract, and/or soy peptone.	-The process is very sensible to any composition in the BSG, this is a problem as the composition of BSG can varies (even if slightly) easily. -Drying and grinding are necessary for this process, the grains cannot be used just like they are.	(Hashemi et al. 2011)

The use of spent brewery grains for Pleurotus ostreatus cultivation and enzyme production	- BSG can be used as a substrate. This can be a cost-effective and sustainable option for P. ostreatus cultivation and enzyme production.	-Optimal enzyme production requires further optimization of the supplementation levels of WB and other ingredients. The complex relationship between substrate composition, enzyme production, and desired enzyme types and quantities may necessitate extensive experimentation and process refinement.	(Gregori et al. 2008)
Enzymatic solubilization of proteins in brewer's spent grain	-Enables the solubilization of proteinaceous material from Brewer's spent grain (BSG), leading to the production of protein concentrates. -Concentrates can serve as valuable ingredients for various industries, including food, animal feed, nutraceuticals, and bioplastics. This diversification of products allows for the exploration of new market opportunities and revenue streams.	-Effectiveness of the technology may depend on various factors such as the quality of the BSG, the type and dosage of enzymes used, and the hydrolysis time. -The technology focuses on protein solubilization but may not address the complete valorization of all components present in BSG. -The cost of enzymes and their stability during long-term storage and industrial-scale processing can be significant factors affecting the overall economics of the technology.	(Treimo et al. 2008)
Sorption of cadmium and lead from aqueous solutions by spent grain	-Potential applicability for the removal of toxic metals from wastewater.	-The sorption capacities of spent grain for cadmium and lead need to be evaluated in comparison to other low-cost biological materials. This assessment is necessary to determine the	(Low, Lee, and Liew 2000)

		competitiveness and potential market position of spent grain as a sorbent, considering factors such as availability, cost, and sorption performance.	
Biological efficiency and nutritional value of Pleurotus ostreatus cultivated on spent beer grain	-P. ostreatus cultivated on BSG substrate exhibited higher nutritional value compared to other reported substrates.	- BSG may require pre-treatment or conditioning to optimize its suitability as a substrate for mushroom cultivation. This complexity hinders its success on a large-scale production model.	(Wang et al. 2001)
Functional and Nutritional Properties of Spent Grain Enhanced Cookies	-BSG enhances the nutritional profile of cookies by increasing fiber content, providing essential minerals, and contributing to a healthier product.	-Additional research are required in order to optimize the inclusion level of BSG and to ensure product stability.	(Oluseyi et al. 2011)
The effect of different enzymes on the quality of high-fibre enriched brewer's spent grain breads.	-Increase in fiber content. -Potential aid of BSG in the prevention of certain diseases.	-Lower softening and loaf volume. -Risk of not customer acceptance.	(Stojceska and Ainsworth 2008)
Application of spent grains to increase porosity in bricks	-Properties like high strength, high porosity and a lower density. -Ideal properties for thermal insulation.	- The inclusion of spent grains in brick production may compromise the durability and structural integrity of the bricks. -The organic content in spent grains can lead to potential issues such as increased moisture absorption, decreased compressive strength, and reduced resistance to weathering and deterioration over time.	(Russ, Mörtel, and Meyer-Pittroff 2005)

Continuous production of pectinase by immobilized yeast cells on spent grains	-Characteristics of BSG's like its shape and its chemical composition provides it with more active sites and it provides a protective environment for the cells.	-Potential diffusion limitations due to restricted access to the immobilized cells. -Very complex operational process.	(Almeida et al. 2003)
Fractions of barley spent grain as media for growth of probiotic bacteria	-Versatile medium for isolation, maintenance, and screening. -Its nutrient-rich composition provides an optimal environment for the growth and survival of various microbial species.	-Requires careful characterization and standardization of BSG fractions for consistent results.	(Novik et al. 2007)
Hydrolysis and fermentation of brewer's spent grain by Neurospora crassa	-Probed effective breakdown of the complex carbohydrates in BSG into fermentable sugars.	-Require specialized equipment and infrastructure to maintain optimal conditions for the growth and activity of Neurospora crassa, this adds ups significantly to the capital and operational costs.	(Xiros et al. 2008)
Enhanced ethanol production from brewer's spent grain by a Fusarium oxysporum consolidated system	-The consolidated system involving Fusarium oxysporum allows for the simultaneous breakdown of complex carbohydrates in BSG and conversion into ethanol, simplifying the overall production process.	-High requirement for large amounts of enzymes to convert cellulose into fermentable sugars. This high enzyme demand has a significant impact on the cost-effectiveness of the technology.	(Xiros and Christakopoulos 2009)
Malt and beer-related by-products as potential antioxidant skin-lightening	-The extraction process uses water under moderate conditions which aligns with green chemistry principles.	- High variability depending the composition of the raw material. This may affect the consistency and reproducibility of	(Almendinger, Rohn, and Pleissner 2020)

agents for cosmetics		the extracted bioactive compounds.	
Potential of Brewer's Spent Grain as a Potential Replacement of Wood in pMDI, UF or MUF Bonded Particleboard	-The proposed product could be used in non-load-bearing panels for interior use in dry conditions, with high dimensional stability and stiffness.	-To improve the efficiency of BSG, higher amounts of BSG should be further studied in combination with innovative glues. -Achieving optimal compatibility between BSG particles and traditional wood particles can be challenging due to differences in their physical and chemical properties leading to quality problems.	(Barbu et al. 2021)
Brewing By-Products as a Source of Natural Antioxidants for Food Preservation	-The technology has potential for use in protecting food systems against oxidation.	-The use of BSG for natural antioxidants may require additional processing steps, which can increase the cost and complexity of the technology.	(Codina-Torrella, Rodero, and Almajano 2021)
Extrusion of brewers'spent grains andapplication in the production of functionalfood. Characteristics of spent grains andoptimization of extrusion	-Obtention of a value-added product. -The technology can potentially contribute to the prevention of diseases such as cancer, diabetes, gastrointestinal disorders, and coronary heart disease.	-Ensuring consistent quality and desired properties of BSG for functional food production may require careful sourcing and quality control measures. -Consumer acceptance and market demand for functional food products derived from BSG may vary.	(Ivanova et al. 2017)
Brewer's Spent Gr s Spent Grain as a F ain as a Functional Ingr unctional Ingredient for Br edient for Breadsticks eadsticks	-BSG is rich in dietary fiber, proteins, and other bioactive compounds. Incorporating BSG in breadsticks can enhance their nutritional profile, making them a healthier option	-Ensuring consistent quality and properties of BSG as an ingredient may require careful sourcing, standardization, and quality control measures.	(Kténioudaki et al. 2012)

	compared to traditional breadsticks made solely with wheat flour.		
Nutritional composition of black soldier fly larvae feeding on agro-industrial by-products	- BSF larvae reared on BSG have high crude protein content, making them a potential new source of nutrient-rich and sustainable animal feed ingredients.	-The nutritional quality of BSF larvae reared on BSG may vary depending on the type of BSG used. -The effect of substrate, supplementation, and their interaction on the nutritional composition of BSF larval body composition is significant, which means that the nutritional quality of the larvae may be affected by the type and amount of supplement used.	(Chia et al. 2020)

Upon comparing the various options, it becomes evident that scalability and sensitivity to BSG composition are the primary challenges in BSG valorization. Among the evaluated alternatives, black soldier fly stands out as a promising solution due to its capacity to process substantial volumes of organic sources and its low sensitivity. Moreover, BSF technology is readily available at an industrial scale and commercially accessible, while BSG has already proven to be a compatible feeding source for it (Scala et al. 2020). Consequently, this technology has been chosen for further in-depth exploration and feasibility analysis.

Exploring the use of Black Soldier Fly Larvae as an alternative for BSG by-product valorization

In recent years, there has been growing interest in the use of insects as a sustainable and environmentally-friendly alternative source of protein for feeding. Among them, the black soldier fly, or *Hermetia illucens*, is one most used insect used for bioconversion technology due to its high protein content and its potential use as a feed supplement (Shahida Anusha Siddiqui et al. 2022).

The following pages present the new circular value change proposed, consisting on supplementing BSG from the brewery production site to a black soldier fly larvae farm for the production of high-quality protein ingredients for feed and pet food production.

The circular value chain proposed: Black soldier larvae (BSF) as a solution

Black Soldier Fly is a fascinating insect that is gaining increasing attention for its potential to convert organic by-products into high-quality nutrients for animal feed (Salam et al. 2022). BSF stands for Black Soldier Fly (Diptera: Stratiomyidae), which is a type of insect that is native to America and can be found in tropical, subtropical, and temperate regions (Beesigamukama et al. 2021). This insect has a great ability to feed from a wide range of organic matter compositions, including food waste, manure, meat processing waste, brewery spent grains waste, bakery waste and agricultural residues (Banks, Gibson, and Cameron 2014). This versatility allows the utilization of a variety of waste streams for its growth, giving an alternative use for byproducts.

The utilization of BSF as a by-product management alternative offers several significant advantages. For instance, its potential for protein production is particularly high, as BSF larvae consist of approximately 35% protein and around 30% crude fat on a dry mass basis (Cappellozza et al. 2019). Furthermore, the incorporation of by-products through BSF utilization has been shown to effectively mitigate risks associated with material accumulation, with potential reductions of up to 80% (Rindhe et al. 2019). Additionally, the residue generated from insect farming can be further valorized as soil fertilizer due to its high nutrient content, providing an additional benefit (Ravi et al. 2020). Another advantage lies in the accessibility and simplicity of the production setting, as the utilization of BSF does not require sophisticated high-end technology, making it easy to operate in addition to its high potential for large-scale production (Veldkamp and Bosch 2015).

Traditional processing method used for BSF farming

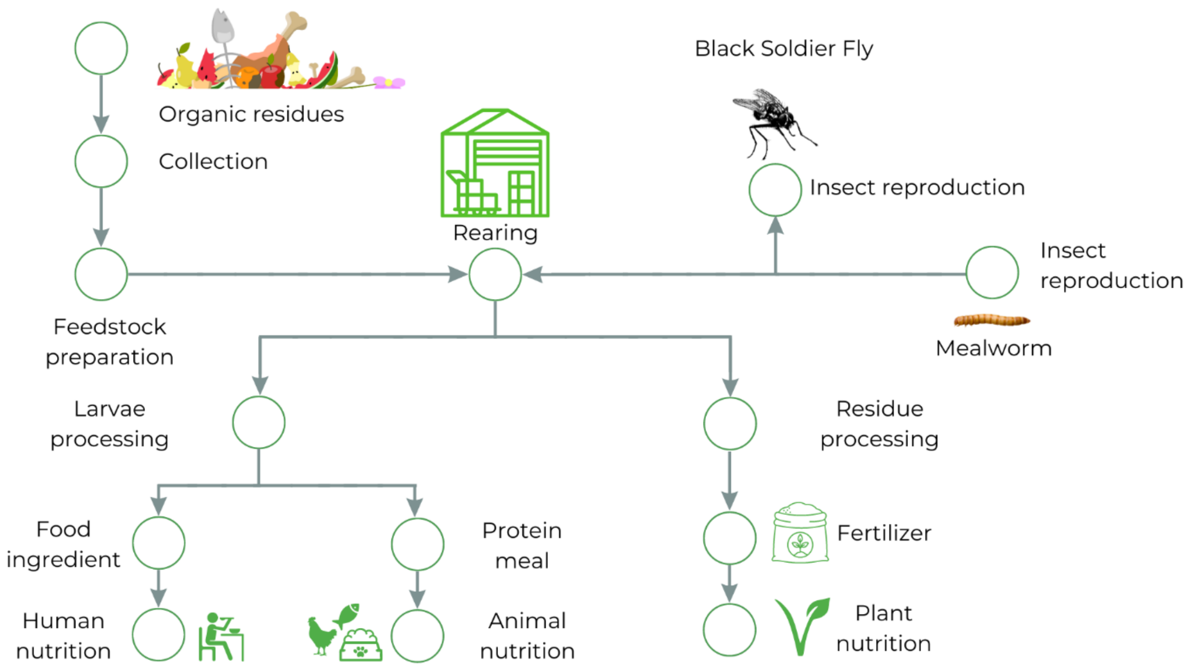
The engineering process for protein production from BSF farming involves three main stages: pre-treatment, treatment, and post-processing (Vo 2020). In the pre-treatment stage, the collected organic residues undergo a thorough inspection to ensure the absence of hazardous materials and inorganic substances. Once this verification is complete, the residues are prepared for further processing through particle reduction, mixing, and homogenization.

Subsequently, the organic residues are inoculated with reared BSF larvae, initiating the treatment phase. During this stage, the young larvae feed on the substrate and effectively convert it into valuable protein-rich biomass (Purkayastha and Sarkar 2022).

Upon reaching maturity, the larvae are harvested, marking the transition to the post-processing stage. This phase involves refinement processes where they undergo a termination process followed by a drying process.

Finally, there is refining of the larvae step that will create the high in protein final product, and the residue remaining be repurposed as a nutrient-rich soil fertilizer. An illustrative depiction of this engineering process can be found in **Figure 5**, providing a visual representation of the aforementioned steps involved.

Figure 5: Schematic production process of food and feed derived from BSF



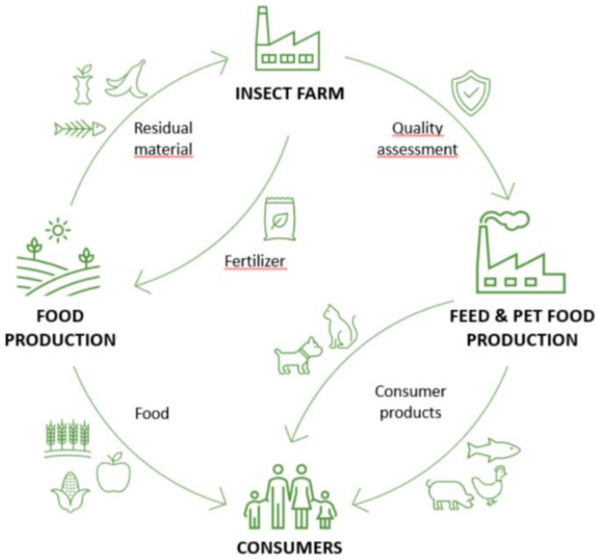
Benefits of the circular value chain with BSF

Due to all the characteristics and benefits previously mentioned, the proposed solution for the Slovenian brewery suggests utilizing the residual material (BSG) as a feed for Black Soldier Fly in an insect farm. With this model, the beer producer can utilize BSG as a feed for BSF, instead of using it for the current low-value application of animal feed. By this, the beer producer can now redirect it towards pet food production which is a higher value application (Mutafela 2015).

On the other hand, the insect farmer can benefit from this model by substituting commercial feeding sources with BSG, which would readily available from the beer producer in significant and constant quantities. It is important to note that the complexity of the operations and the GHG emissions associated with the logistics of today's practices within the company for BSG valorization will be positively impacted by reducing the number of off takers and the number of shipments.

Notably, the residues left after the BSF feeding process can be repurposed as high-quality organic fertilizer (Amrul et al. 2022). Thus, it can be reintegrated into agricultural practices for the brewery's agricultural raw materials. This model closes the loop, promotes sustainability and allows circularity within the brewery's supply chain. **Figure 6** illustrates this new circular value chain proposed for the beer producer.

Figure 6: *Schematic representation of the new circular value chain with BSF as the valorization method proposed for the BSG by-product*



The environmental impacts of using BSF for biowaste conversion

The proposed valorization method for using brewer's spent grain as a substrate for black soldier fly larvae, aimed at producing high-protein products, presents several environmental advantages. Various studies have examined the environmental impacts of bioconversion of organic wastes into BSF biomass and have consistently shown that using BSG as a feed source for BSF larvae results in lower environmental impacts compared to alternative uses such as traditional animal feeding (González-García et al. 2018; Surendra et al. 2020).

When comparing the environmental footprint of BSF rearing to conventional livestock production, it becomes evident that insects require fewer resources to produce the same amount of protein. As shown in **figure 7**, insect farming requires significantly less food, land, water, and energy relative to livestock production (Moruzzo, Mancini, and Guidi 2021). The climate impact of insect rearing in terms of greenhouse gas emissions and ammonia emissions is also considerably smaller. For example, the land area required to produce 1 kg of protein is significantly lower for insects compared to livestock (Goodland and Anhang 2009). Furthermore, insects demonstrate high efficiency in converting ingested food into body mass, outperforming livestock in terms of feed conversion efficiency (Gahukar 2016).

Moreover, the environmental benefits extend beyond protein production, as BSF larvae have shown the potential for bioremediation by degrading pesticides and pharmaceuticals present in organic waste streams (Kim et al. 2021). Overall, the utilization of BSG as a substrate for BSF represents a more environmentally favorable valorization method compared to the current method that the Slovenian company is using today.

Figure 7: Comparison of farmed insect to livestock's environmental impact: a) Land usage, b) CO2 emissions, c) Water usage, d) Efficiency (Gahukar 2016)

Legislation landscape: Analysis of regulatory standards for insects as feeding ingredients

In order to ensure a successful implementation of the proposed technology, it is imperative to conduct an examination of the legal context. Within this framework, there exist several regulations that support the utilization of black soldier fly (BSF) in various applications worldwide (Sogari et al. 2019). As the company is located within the European Union territory, this has been as the regulatory system of relevance. Thus, the following section presents a concise review of the main elements of the existing legislation on the use of insects as feed in the European Union.

Regulation (EU) 2017/893 has an a important role in shaping the regulatory landscape pertaining to insects as a valuable resource (EU 2017). The regulation possess a dedicated section specifically addressing insects and insect products. It authorizes the feeding of non-ruminant processed animal protein to aquaculture animals. This legislation allows the use of seven different species and BSF is among them. The regulation also specifies the substrates allowed as feed for insects, being the use of BSG in compliance with it. In addition, The Food and Agricultural Organization (FAO) recommends that insect species suitable for feed are those that can be mass-reared on an industrial scale, with a minimum reach of 1, 000 kg per day of insect fresh weight (van Huis 2013)

On the other hand, in 2009 Regulation (EC) 1069/2009, which pertains to EU Animal By-Products (ABP) legislation, authorizes the use of processed live terrestrial invertebrates and dead terrestrial invertebrates as feed materials (EC 2009). These purposes include feeding zoo and circus animals, reptiles, birds of prey, wild animals, fur animals, and fishing bait. However, such authorization is contingent upon ensuring the absence of health risks (Ravi et al. 2020).

Additionally, point 3(iv) of Chapter II of Annex XIII in Regulation (EU) 142/2011, allows the use of frozen or dried insects for pet food animals such as dogs and cats, subject to the specific authorization by national authorities (EU 2011).

For most regulations, the pre-requisites for utilization of insect sourced protein is dependent on complying with the limits on undesirable substances (Sogari et al. 2019). In general, the regulations set limits for heavy metal bioaccumulation (especially cadmium and arsenic) in the insect-based feed composition. Thereby, minimizing the possible risk of, allergenic hazards and microbial and contamination (Van der Fels-Klerx et al. 2018).

Technical analysis: feasibility of cultivating BSF with BSG

As aforementioned, Black Soldier Fly (BSF) larvae have a strong ability to grow when they consume organic waste material (Rindhe et al. 2019). Its diet can include various types of organic waste such as leftover food scraps, agricultural residues, and other decaying organic materials, as they are not highly selective in their feeding habits. However, the final the nutritional composition of BSF larvae is significantly influenced by the composition of the feed they consume (Diener, Zurbrügg, and Tockner 2009). In addition, the yield and quality of BSF larvae are subject to variations based on their feed sources (Shahida Anusha Siddiqui et al. 2022).

Against this background, it is crucial to evaluate the feasibility of utilizing BSG as a feed source for BSF larvae. Several studies have contributed to our understanding in this area. For instance, a study assessed using brewery-spent grain to feed black soldier fly larvae finding it completely viable (Chia et al. 2020). Another study revealed that BSF larvae reared on BSG exhibited higher nutritional quality compared to larvae reared on other substrates (Meneguz et al. 2018). Additionally, Zhang et al. conducted a research indicating that the use of BSG as a substrate for the bioconversion process by BSF resulted in a significant increase in larval production (Zhang et al. 2023). Researchers such as M. Tschirner and A. Simon (2015) have also observed rapid growth and high survival rates in BSF larvae fed with an abundance of organic waste, including BSG. (M. Tschirner and A. Simon 2015).

Based on the literature information and the evaluation of BSG composition **(Table 5),** it becomes evident that this particular by-product from the beer production process can effectively serve as a nutrient-dense meal for BSF larvae when incorporated into their diet. One of the advantages of using BSG for BSF feeding is that the brewing process utilizes ingredients approved for human consumption. This aspect presents the potential for developing products that can meet health regulations and standards

(Fărcaş 2014). Furthermore, the composition of BSG suggests that it holds the potential to offer several benefits, including the reduction of certain health risks, primarily due to the presence of bioactive compounds (Lynch, Steffen, and Arendt 2016). These characteristics and the great availability if BSG as very high quantities of them are produced annually make BSG an ideal candidate for feeding Black Soldier Fly larvae.

Table 5: Composition of the brewers' spent grains produced in the brewery

Dry matter (g/kg)	230
Crude protein (g/kg DM)	265
Crude fibre (g/kg DM)	160
Ether Extract (crude fat) (g/kg DM)	105
N-free extractives (g/kg DM)	427
Ash (g/kg DM)	43
Amino acids (g/kg DM)	
Lysine	9,3
Methionine	5
Met + Cys	10,1
Threonine	9,3
Tryptophan	3,4
Major minerals (g/kg DM)	
Calcium	4,5
Phosphorus	6
Magnesium	
Sodium	0,5
Potassium	0,7

Market analysis: feasibility of valorizing BSG in an insect farm from a business perspective

An analysis of the current market landscape is crucial to identify potential opportunities for the proposed valorization method.

The industrial insect production market, for both food and feed sectors, is projected to grow by 24.4% in the coming years (Gasco et al. 2020). This growth trajectory indicates a global production estimate of over 730,000 tonnes by 2030, while the current annual production in the European Union stands at approximately 6,000 tonnes. Projections suggest that insect farms will contribute around 10% of the protein share by 2025, indicating a significant shift towards sustainable and high-protein feed sources (Gasco et al. 2020). This optimistic outlook is driven by increasing consumer demand and businesses recognizing the economic and environmental benefits of such practices. Favorable government policies and evolving consumer behavior is projected to enhance the growth potential of the market (Siddiqui et al. 2023).

Several companies, such as Hermetia GmbH, Bioflytech, and EnviroFlight, are already engaged in BSF larvae production, showcasing their involvement and growth in the high-value protein sector (Surendra et al. 2020). Despite the unavailability of specific financial details of these companies, their presence and expansion shed light on the economic viability of producing protein products from BSF.

The utilization of BSF-derived proteins in the pet food industry serves as a notable commercial example that has gained significant popularity. The European market witnessed the launch of the first insect-based dog food back in 2015, initially dominated by start-ups and regional companies. However, as time progressed, an increasing number of companies began developing insect-based products for pet food. By 2018, Europe saw the marketing of at least 12 insect-based pet food brands, indicating the growing momentum in this sector (Bosch and Swanson 2021). Today, global companies like Nestle and Mars have also entered this domain, incorporating BSF fat into their pet food formulations and the pet food market stands as the largest market for insect proteins in Europe. (Mouithys-Mickalad et al. 2021).

SWOT analysis for using BSF as a valorization pathway for BSG

With the aim of obtaining a comprehensive understanding of the valorization method for utilizing BSG as a substrate for Black Soldier Fly (BSF), a SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis was conducted **(Figure 7).** The observations and inferences presented in this analysis are derived from previously documented literature and the specific topics covered in this review. Similar analysis that provide insights into the strengths, weaknesses, opportunities, and threats associated with the utilization of insects for protein production can be find in the literature (Gasco et al. 2020).

Figure 7: *Strengths, weaknesses, opportunities, and threats (SWOT) analysis of the proposed value chain that considers feeding BSF with BSG*

Strengths

Sustainable solution - The proposed circular economy approach offers a sustainable and environmentally-friendly solution for BSG valorization, addressing the challenge of organic waste production in the brewing industry (Chia et al. 2018).

Resource efficiency - The utilization of BSF larvae for BSG valorization maximizes resource efficiency by converting organic waste into valuable protein-rich insect biomass. In fact, several investigations have documented the use of BSF as a sustainable and resource efficient alternative (Bosch et al. 2019).

Feasibility and scalability - Black Soldier Fly (BSF) technology is readily available at an industrial scale and has been successfully implemented for organic waste management in various contexts, making it a feasible and scalable solution for BSG valorization (Rehman et al. 2023).

Nutritional benefits - BSG has been identified as a suitable and nutrient-rich feed source for BSF larvae, leading to the production of high-quality protein and other valuable by-products (Chia et al. 2020). In general, BSF exhibit a rich protein content, ranging from 30% to 68% on a dry matter basis (Finke 2015). They can also be can be considered as a good source of vitamins, especially vitamin B12, and bioavailable minerals (Clr et al. 2016).

Closed-loop system - The proposed circular value chain allows for the integration of BSG by-products, such as residual material and organic fertilizer, back into the brewing industry, creating a closed-loop system that promotes sustainability and circularity (Allegretti et al. 2022).

Weaknesses

Operational challenges - Introducing the new method of utilizing BSG as a substrate for BSF requires adjustments to the existing production and by-product management systems within the brewery. This transition may involve creating new suppliers internally, documenting the new procedure, and implementing new partnerships for the integration of the new process.

Regulatory compliance – Even though, the utilization of BSG as a substrate for feeding BSF larvae is allowed by the European regulatory framework, its implementation in Slovenia may require a second verification of compliance with the specific regulations and standards of the country (Bosch et al. 2019).

Opportunities

Market potential - The circular economy model for BSG valorization using BSF presents opportunities for the development of new value-added products, such as pet food which can tap into growing market demand for sustainable and eco-friendly solutions. In fact, the production of pet food from insect protein has been reported as a niche market with one of the highest growth (Bosch and Swanson 2021).

Economic viability - The utilization of BSG as a feed source for BSF larvae presents an opportunity for the beer producer to generate additional revenue streams and enhance the overall economic sustainability of the brewery. By converting BSG, into a valuable resource through BSF, the brewery can tap into new market opportunities and access to potential economic gains.

Reduction of logistics complexity – By establishing a partnership with a single on-site entity, the producer can streamline supply chain operations and simplify the management of BSG. This consolidation not only reduces logistical challenges but also enables better quality control and coordination throughout the valorization process. The collaboration with the on-site partner promotes knowledge sharing, innovation, and the exploration of new product development opportunities. Overall, this opportunity allows the BSG producer to optimize operations, enhance efficiency, and potentially unlock additional revenue streams in the circular economy model.

Threats

Competition from alternative technologies - One potential threat to the implementation of the valorization model is the emergence of more efficient technologies in the future. As the field of sustainable waste management and resource utilization continues to evolve, it is possible that alternative methods or technologies could be developed that offer higher efficiency, lower costs, or improved environmental performance compared to BSF (Jain et al. 2022).

Fluctuating demand from buyers - One significant threat to the BSG producer could be the possibility of fluctuating demand from its buyers. If the BSG producer relies on a unlimited number of buyers for its product without any kind of partnership or contract, any changes in their demand or purchasing behavior can have a direct impact on the producer's business operations and revenue.

Conclusions, perspectives and recommendations

In conclusion, there is a growing recognition of the importance of reusing agro-food industrial by-products, driven by economic and environmental considerations. Brewers' spent grain, as a significant by-product generated by brewing companies, offers immense potential for valorization. However, the current utilization of BSG remains limited, primarily confined to animal feed or disposal in landfills. Therefore, the development of innovative circular economy techniques for the valorization of this abundant agro-industrial by-product is of great significance, especially considering the substantial quantities of spent grain produced annually.

This research aimed to explore sustainable strategies for brewers' spent grain management in the brewery sector, considering the challenges faced by companies in finding environmentally friendly yet industrial, commercial, and economically feasible valorization pathways. The study utilized various sources of data to identify potential solutions and contributes with insights for enhancing the sustainability of high-scale breweries' value chains.

The research findings offer valuable knowledge regarding the current state of waste management options for BSG, providing a comprehensive understanding of their existing advantages and limitations. Unfortunately, while these alternatives showed promising results in laboratory-scale closed-loop systems, most of them are still in the developmental stage and not ready for implementation in large-scale industrial processes.

Considering these limitations, a new model incorporating black soldier fly and circular economy approaches was selected as a potential solution. Moreover, the feasibility of implementing the proposed value chain model was thoroughly investigated. For this, a systematic analysis was conducted to confirm the viability of this sustainable strategy in effectively managing the brewery's by-product generation. The research highlighted the benefits of the proposed model, emphasizing its potential to enhance the circularity of the value chain and facilitate the efficient utilization of the brewery's most generated by-product.

On the other hand, prior to implementing the new BSG valorization strategy, it is advisable to conduct a thorough review aimed at organizing internal processes and allocating necessary resources with the aim to develop this idea within the company. This preparatory step will facilitate the analysis of operational practices that would be involved for the implementation of the strategy. Moreover, it is recommended to conduct further analyses, specifically a life cycle analysis that considers the proposed value chain, to gain deeper insights into the potential reduction of environmental impacts.

In general, the research demonstrates a positive outcome in terms of the feasibility of implementation. However, it is crucial to conduct additional feasibility studies and analyses to broaden the understanding of the by-product valorization solution's potential. To that end, it is recommended to pursue further research in the following key directions:

- Future studies should delve into technical analyses related to BSF, focusing on specific growth behavior of the larvae when fed with the BSG waste from the Slovenian brewery.
- Additional research should expand on the assessment of the new process's environmental impact across various spheres, encompassing not only greenhouse gas emissions but also factors such as acidification, eutrophication, and ecotoxicity.
- Continuous identification of other breweries implementing this alternative in different regions and contexts is advised for benchmarking purposes.
- Subsequent investigations to validate the social implications of the BSF alternative are strongly encouraged to foster a comprehensive comprehension of the impacts related to the valorization of BSG.

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