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CIRCULAR ECONOMY IN CRAFT BREWERIES: INNOVATIVE STRATEGIES FOR WASTE REDUCTION AND SUSTAINABLE DEVELOPMENT

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Abstract: The craft brewery industry is growing rapidly but faces sustainability challenges due to waste, water use, and emissions. This study examines circular economy strategies in craft breweries through case studies, focusing on waste reduction, by-product valorisation, and sustainable operations. The findings reveal that repurposing spent grains, using renewable energy, and fostering local partnerships enhance both environmental and economic performance. Policy support and education are crucial for broader adoption. Implementing circular practices not only reduces waste and costs but also strengthens brand reputation and industry resilience, demonstrating the viability of sustainability-driven business models in the craft brewing sector.

Keywords: circular economy, craft breweries, waste valorisation, sustainability, industrial symbiosis, business model.

1. INTRODUCTION

The circular economy (CE), also known as the closed-loop economy [Kara et al. 2022], is gaining increasing importance across various industrial sectors, including the brewing industry [Lodhi 2024]. CE is a business model aimed at minimising raw material consumption and reducing waste generation, with the broader goals of lowering greenhouse gas emissions and optimising energy use in economic processes [PARP 2025]. Although conceptually straightforward, implementing CE requires a deliberate and thoughtful design of production processes. Ideally, waste does not exist in a circular model – every material is treated as a potential input for another cycle [PARP 2025].

The brewing sector represents a significant component of the global economy. In 2023 alone, it contributed 0.8% to the global GDP, amounting to an impressive $878 billion [ZPPP Browary Polskie 2025]. Poland, one of Europe's leading beer producers, generated approximately $6 billion in added value through its breweries,

which support around 120,000 jobs across the country [ZPPP Browary Polskie 2025]. Notably, the influence of breweries extends beyond beer production, impacting interconnected industries such as agriculture, logistics, retail, and gastronomy. This interdependence means that any shifts within the brewing industry carry wide-reaching implications for the broader economic ecosystem [ZPPP Browary Polskie 2025].

There has been a notable resurgence of interest in traditional brewing methods, particularly within craft breweries, in recent years. Unlike large-scale industrial beer producers, craft breweries prioritise quality, authenticity, and, often, environmental responsibility [Biskupski 2024]. Their smaller scale and artisanal nature provide a unique opportunity to adopt and implement sustainable and circular practices more flexibly and creatively.

At the same time, consumer preferences are evolving. Market research shows that over half of consumers are willing to pay a premium for products – especially food and beverages – that are produced naturally rather than through mass industrial processes [Biskupski 2024]. This growing demand for authenticity and sustainability offers craft breweries a competitive edge if they can successfully embed circular economy principles into their operations.

Despite their sustainable ethos, the expansion of the craft brewing sector has also led to considerable waste generation, including spent grains, wastewater, and CO_2 emissions. Circular economy principles offer a promising framework for addressing these challenges by enabling breweries to reduce waste, valorise by-products, and improve both environmental and financial performance. This study explores how circular economy practices can be adopted within craft breweries, focusing on waste minimisation, resource valorisation, renewable energy integration, and operational innovation. It also examines the potential of industrial symbiosis, policy support, consumer engagement, and education as critical enablers in fostering a more circular and sustainable craft brewing industry.

This comprehensive analysis will provide actionable insights and case studies demonstrating successful implementations, ultimately encouraging more craft breweries to adopt these sustainable practices and contribute to a greener future. The findings of this study will not only highlight the economic benefits of adopting sustainable methods but also inspire a cultural shift within the industry, promoting a deeper commitment to environmental stewardship among craft brewers and their communities.

By showcasing innovative approaches and best practices, this research aims to actively empower stakeholders in the transition towards a circular economy, ensuring that sustainability becomes a central part of the craft brewing narrative. This holistic approach will enhance craft breweries' reputation and create a ripple effect, encouraging consumers to support environmentally conscious brands and fostering a community that values sustainability as a core principle. As a method, the narrative (traditional) review was applied, which consisted of four phases: (1) design, (2) execution, (3) analysis, and (4) writing [Templier and Paré 2015; Snyder 2019].

This paper consists of five sections: Section 2 is about implementing CE principles in craft breweries to reduce waste and improve sustainability, and it is divided into seven subsections, which present various approaches to CE implementation in detail. Section 3 describes the case studies of successful implementations of CE practices in breweries. The benefits and challenges of industrial symbiosis in craft breweries are shown in Section 4. Conclusions and recommendations are in Section 5.

2. IMPLEMENTING CIRCULAR ECONOMY PRINCIPLES IN CRAFT BREWERIES TO REDUCE WASTE AND IMPROVE SUSTAINABILITY

Craft breweries can significantly reduce waste and enhance sustainability by adopting circular economy principles, emphasising resource efficiency, waste valorisation, and integrating renewable energy [Mainardis, Hickey and Dereli 2024]. These principles align with the growing demand for environmentally responsible practices in the brewing industry [Bolwig et al. 2019; Ahuja et al. 2024].

2.1. Valorisation of brewery by-products

One of the most significant opportunities for craft breweries lies in the valorisation of by-products, particularly brewers' spent grain (BSG), which constitutes uckey andp to 85% of a brewery's total waste [Ortiz et al. 2019; Mainardis, Hickey and Dereli 2024].

BSG is rich in proteins and fibres, making it a suitable animal feedstock. It can be sold to animal feed producers or rural farmers, reducing landfill use and generating revenue [Sperandio et al. 2017; Filko 2022]. However, its use is limited by the availability of local farms, especially in urban areas.

Composting is another traditional method, converting BSG into nutrient-rich soil amendments [Lech and Labus 2022; Mainardis, Hickey and Dereli 2024]. Anaerobic digestion of BSG can produce biogas (methane and CO2), which can be used to generate heat or electricity for the brewery; by adopting this strategy, the dependence on fossil fuels is minimised and emissions of greenhouse gases are decreased [Ortiz et al. 2019; Allegretti et al. 2022; Idowu et al. 2022; Rawalgaonkar 2023; Mainardis, Hickey and Dereli 2024].

Thermochemical conversion methods transform BSG into biochar or syngas, which can be used as energy sources or soil amendments, offering economic and environmental benefits [Sperandio et al. 2017; Ortiz et al. 2019].

BSG can be repurposed in innovative ways to create value-added products. BSG can be processed to extract valuable compounds such as proteins, fibres, and phenolics, which can be used in food, cosmetics, or pharmaceutical applications. For instance, BSG can be converted into functional food ingredients or biopolymers [Lech and Labus 2022; Pasquet, Villain-Gambier and Webouet 2024]. Finally, spent

yeast and hops can be processed to extract valuable compounds like antioxidants and essential oils, which can be sold to the cosmetic or pharmaceutical industries [Chattaraj et al. 2024].

However, as suggested by Łukaszewicz et al. [2024], there is a need for specialised facilities with the collaboration of multiple small breweries because of the high costs of equipment for yeast biomass fractionation. These facilities would collect yeast biomass from breweries, and their production would remain flexible, as the required equipment can be used to purify various yeast biomass fractions. Processing is economically viable only when market conditions allow for profitable pricing of yeast-biomass-derived products. The growing demand for vegetarian and functional foods and industrial advancements may favour yeast biomass processing in the future [Łukaszewicz et al. 2024].

2.2. Wastewater and carbon dioxide valorisation

In addition to BSG, breweries generate large volumes of wastewater and carbon dioxide. Brewery wastewater can be treated and reused for cleaning, irrigation, or brewing. Membrane bioreactors or anaerobic digestion can recover water and energy from wastewater [Filko 2022]. Carbon dioxide, a by-product of fermentation, can be captured and reused in various applications, such as the carbonation of beer, the production of sparkling water, or as a raw material in the chemical industry [Rawalgaonkar et al. 2023; Albert and Kelemen-Erdős 2024].

2.3. Industrial symbiosis and resource sharing

Industrial symbiosis, in which waste from one process is a resource for another, is another cornerstone of circular economy practices in craft breweries. For example, breweries can partner with local farmers to supply spent grain as animal feed or with biorefineries to convert waste into bio-based products [Filko 2022]. Similarly, wastewater and CO2 from fermentation can be treated and reused in other industrial processes, such as irrigation or carbonation [Rawalgaonkar et al. 2023; Albert and Kelemen-Erdős 2024]. Such partnerships foster a circular economy, enhancing resource efficiency and sustainability [Julkovski et al. 2024].

2.4. Energy recovery and renewable energy integration

Energy recovery is a critical component of circular economy practices in breweries. Anaerobic digestion of organic wastes, such as BSG and yeast, can produce biogas, which can be used to power brewery operations [Ortiz et al. 2019; Rawalgaonkar et al. 2023]. Additionally, breweries can integrate renewable energy sources, such as solar or geothermal energy, to power their operations, further decarbonising their processes [Julkovski et al. 2022; Mainardis, Hickey and Dereli 2024]. Geothermal energy can also be applied to heat and cool breweries [Mainardis, Hickey and Dereli 2024]. Biogas produced from BSG or wastewater can power brewery operations,

reducing energy costs and greenhouse gas emissions [Sperandio et al. 2017; Rawalgaonkar et al. 2023].

Improving energy efficiency is also important when implementing circular economy practices in breweries. Energy efficiency can be achieved by optimising brewing processes, such as fermentation and maturation, which are energy intensive. Exploring alternative yeast strains that ferment at higher temperatures can also reduce energy consumption [Bowler et al. 2024]. Heat exchangers and recovery systems can capture and reuse heat from brewing processes, reducing energy consumption [Albert and Kelemen-Erdős 2024; Ho, Thach and Bui 2024]. Optimising brewing processes, such as reducing water usage and minimising batch sizes, can lower energy demand and waste generation [Julkovski et al. 2022; Albert and Kelemen-Erdős 2024].

2.5. Water efficiency and recycling

Water is a critical resource in brewing, and its efficient use is essential for sustainability. Craft breweries can implement water recycling systems to reuse process water for cleaning, cooling, or even in subsequent brews [Albert and Kelemen-Erdős 2024; Ho, Thach and Bui 2024], reducing freshwater demand and operational costs [Zacharof 2021]. Membrane filtration and reverse osmosis can treat wastewater to meet reuse standards, reducing both water consumption and wastewater discharge [Albert and Kelemen-Erdős 2024; Ho, Thach and Bui 2024].

2.6. Packaging of craft brewery products

The environmental implications of using circular packaging for craft brewery products are multifaceted, involving considerations of material choice, lifecycle impacts, and consumer behaviour. Circular packaging, such as reusable steel kegs, offers significant environmental benefits over single-use options, primarily due to their durability and potential for multiple reuse cycles, which reduce the need for new materials and lower overall emissions [Martin et al. 2022]. However, the environmental performance of these systems is highly dependent on the logistics of their use, such as the distance between breweries and markets, which can affect the sustainability of heavier steel kegs compared to lighter plastic alternatives [Martin et al. 2022]. The integration of recycling and reuse, two of the CE principles, is crucial in reducing the environmental footprint of packaging. For instance, PET kegs have been identified as a more sustainable option than glass bottles and aluminum cans due to their lower environmental impact during the distribution phase and their potential for recycling [Bowler et al.; Marrucci, Daddi and Iraldo 2024].

Adopting circular business models can further enhance sustainability by optimising the lifecycle impacts of packaging through strategies like closed-loop recycling systems and secondary raw materials [Niero et al. 2017; Sigüenza et al. 2020]. Moreover, consumer behaviour is crucial to the success of circular packaging

systems. Effective recycling and reuse depend on consumer participation, which can be influenced by factors such as awareness, infrastructure availability, and policy support [Corona, Tunn and van den Broek 2023]. Therefore, integrating consumer behaviour insights into lifecycle assessments can improve the design and implementation of circular packaging systems, ensuring they are both environmentally and economically viable [Corona, Tunn and van den Broek 2023]. The transition to circular packaging in the craft brewery sector requires a comprehensive approach that considers material selection, lifecycle impacts, and consumer engagement to achieve significant environmental benefits [Karayılan et al. 2021].

2.7. Circular business models and innovation

Adopting circular business models can drive innovation and sustainability in craft breweries. For example, breweries can adopt product-as-a-service models, where equipment is leased rather than sold, encouraging resource efficiency and reuse [Julkovski et al. 2022, 2024; Puig, Navarro-Sanfelix and Cantarero 2024]. Additionally, breweries can engage consumers in circular practices by promoting refillable packaging or take-back programs for bottles and cans [Julkovski et al. 2022; Puig, Navarro-Sanfelix and Cantarero 2024]. It should be noted that from October 2025, all metal cans with a capacity of up to 1 litre will be covered by the deposit system. And even craft breweries selling beer in cans must prepare to participate in the deposit system. In the currently adopted model of the deposit system, the disposable glass bottle is not covered by this system. For breweries operating on disposable glass bottles, the introduction of the deposit system will not change anything [Act of June 13, 2013].

Strengthening relationships with local suppliers and consumers can enhance resource circularity and reduce transportation-related emissions [Julkovski et al. 2022; 2024]. Academic institutions and business associations can help spread the word about cutting-edge circular economy strategies [Gruba et al. 2022; Ho, Thach and Bui 2024].

Investing in technologies such as anaerobic digestion, biogas recovery, and advanced wastewater treatment can improve resource efficiency and reduce waste [Rawalgaonkar et al. 2023]. Microbial fermentation and enzyme-aided conversion of BSG can unlock new valorisation pathways, producing high-value products such as biofuels, biopolymers, and food additives [Lech and Labus 2022; Ahuja et al. 2024]. Leveraging digital tools for process optimisation, energy monitoring, and supply chain management can enhance the circularity of brewery operations [Albert and Kelemen-Erdős 2024; Ho, Thach and Bui 2024].

Since Scope 3 emissions „all other emissions along the supply chain: upstream emissions (purchased goods and services) and downstream emissions „sold goods and services" [WRI/WBCSD 2004]; Stenzel and Waichman (2023) dominate the carbon footprint in breweries, focusing on reducing emissions from the entire value

chain, including procurement of materials and transportation, is essential. Emission reduction requires collaboration with suppliers and logistics partners to implement more sustainable practices [Cimini and Moresi 2018; Salazar Tijerino et al. 2023]. Reducing supply chain length and enhancing the content of recycled materials are crucial measures for achieving sustainable glass bottle production in the craft beer industry [Wojnarowska et al. 2025].

Encouraging recycling and proper waste management, especially in post-consumer phases, can significantly impact the overall carbon footprint. Breweries should focus on increasing the recycling ratio of packaging materials in their sales areas [Bowler et al. 2024]. Implementing tools like carbon calculators can help breweries benchmark their emissions and identify areas for improvement, and this can drive competition among breweries to appeal to environmentally conscious consumers and accelerate industry decarbonisation [Salazar Tijerino et al. 2023]

[García-Chamizo et al. 2025] examine the role of sustainable practices in the Spanish craft beer industry through a study of 42 breweries. They identify a link between brand identity and sustainability, suggesting that this relationship can advance the circular economy. The study recommends that small artisanal producers use territorial branding models to enhance their sustainability and competitiveness. Craft brewers are encouraged to implement sustainable methods within their production processes, as well as in their brand narratives and regional marketing efforts [García-Chamizo et al. 2025].

Factors such as water conservation, minimising carbon emissions, organic agriculture, and local procurement shape consumer buying decisions in the craft beer sector. Consumers' environmental concerns and attitudes towards sustainability greatly affect their purchasing choices, underlining the importance of conveying these sustainability features to the market [Lourenco and Piotto 2024].

Implementing process innovations such as energy recovery systems, process automation, and proper insulation of tanks and pipelines can further reduce energy use and enhance sustainability in brewing operations [Bowler et al. 2024].

3. CASE STUDIES

Several case studies demonstrate the implementation's success in craft breweries. For instance, La Somniada, a Spanish craft brewer, used 100% renewable energy, recycled water, and valorised all by-products [Puig, Navarro-Sanfelix and Cantarero 2024]. Similarly, the Birraverde project in Italy has demonstrated the feasibility of converting spent grain into biochar and pellets for energy generation, reducing waste and carbon emissions [Sperandio et al. 2017].

Polish breweries have implemented various strategies for managing and reusing brewery waste. These include using spent grain for animal feed, creating human food products like pizza dough and cereal bars, and utilising waste as fertilisers or for biogas production. Such practices highlight the breweries'

commitment to expanding waste management alternatives and enhancing the value of brewery by-products [Bonato et al. 2022].

The brewing industry in Poland, similar to global trends, focuses on sustainability assessments and life cycle assessments to evaluate the environmental performance of beer production; this includes analysing energy use and emissions across different scales of brewing operations, from microbreweries to larger commercial setups [Bonato et al. 2022].

Craft breweries should adopt the proven strategies of large players in the market. Carlsberg Polska examined the carbon footprint in the value chain, and it turned out that the component generating approx. 40% of CO2 emissions is in the packaging process: production, distribution, and disposal of packaging. The most environmentally friendly packaging is returnable glass bottles, whose carbon footprint is 10 times lower than disposable glass bottles [Greszta, Żmudzińska and Zielińska 2023]. It is worth adding that a returnable bottle can survive an average of up to 20 refill cycles. Brown and green glass bottles are most suitable for reusable packaging because they do not show micro-scratches during the packaging turnover. They should be of adequate thickness for product safety reasons to withstand multiple transport and washing cycles [Greszta, Żmudzińska and Zielińska 2023].

As Carlsberg Polska does, a potential strategy to reduce the carbon footprint is to use one returnable bottle design for all brewed beer brands. One-third of the beer produced by Carlsberg Polska reaches consumers in returnable packaging, and the return rate of bottles reaches 90%. Thanks to this, bottles collected in stores do not require additional sorting and can be returned to the brewery for refilling more quickly [Greszta, Żmudzińska and Zielińska 2023]. Another Polish bear producer, Żywiec also decided to change its packaging, replacing all transparent 400 ml bottles of Żywiec Jasne Lekkie with green returnable 500 ml bottles, which in the long term should reduce indirect emissions from Scope 3 [Greszta, Żmudzińska and Zielińska 2023].

4. BENEFITS AND CHALLENGES OF INDUSTRIAL SYMBIOSIS IN CRAFT BREWERIES

Craft breweries can benefit from industrial symbiosis in three key areas: environmental improvements resulting from resource efficiency, economic advantages linked to cost reduction and value creation, and the role of community engagement in enhancing reputation and stakeholder relations. By reusing by-products, breweries reduce waste disposal in landfills and decrease greenhouse gas emissions. Efficient resource use also conserves water and energy, aligning with global sustainability goals [Sehnem et al. 2021]. Recovering and selling by-products generates additional revenue streams. Energy recovery from waste reduces energy costs, while water recycling lowers operational expenses, improving overall profitability [Sperandio et al. 2017; Ortiz et al. 2019]. Engaging in industrial symbiosis enhances a brewery's reputation as an eco-friendly company, which can

draw in eco-aware customers and strengthen community ties, providing a competitive edge [Ness 2018; Veleva et al. 2024].

Many breweries, especially smaller ones, may not be aware of the full potential of industrial symbiosis. Limited knowledge about waste management and reuse opportunities can hinder implementation [Filko 2022; Veleva et al. 2024].

Investing in new technologies for waste recovery can be costly. Smaller breweries may struggle to afford the initial setup despite the long-term cost savings [Veleva et al. 2024].

The absence of clear policies supporting industrial symbiosis can create barriers. Breweries may struggle to adopt circular practices without incentives or guidelines [Sehnem et al. 2021].

5. CONCLUSIONS

The exploration of circular economy principles within craft breweries reveals a transformative pathway for enhancing sustainability and reducing waste in an industry characterised by rapid growth and environmental challenges. By adopting innovative strategies such as valorising by-products, engaging in industrial symbiosis, and integrating renewable energy solutions, craft breweries can significantly diminish their ecological footprint while simultaneously creating new economic opportunities. The case studies presented, alongside the examination of successful implementations, highlight the potential for breweries to not only prosper in a competitive market but also make a positive contribution to their communities and the environment.

Furthermore, policy, education, and consumer engagement are paramount in facilitating this transition, underscoring the collaborative efforts necessary for fostering sustainable practices. As craft breweries embrace these circular economy practices, they stand to reinforce their reputation as responsible stewards of the environment, ultimately inspiring a broader cultural change in the beverage industry towards sustainability. The findings of this research not only provide actionable insights for stakeholders but also lay the groundwork for future exploration into the challenges and opportunities for a sustainable brewing landscape.

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