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A CRITICAL REVIEW ON INNOVATIVE STRATEGIES FOR BREWERY WASTEWATER VALORIZATION: ADVANCING SUSTAINABILITY IN THE FOOD INDUSTRY

Daniela-Mihaela GRIGORE[1], Maria-Luiza MIRCEA[1], Jamila YEHMED[2], Ionuţ Nicolae RANGA[3], Elena Narcisa POGURSCHI[1]

[1]Faculty of Animal Productions Engineering and Management, University of Agronomic Sciences and Veterinary Medicine of Bucharest, 59 Marasti Blvd, District 1, Bucharest, Romania
[2]Dry Land Farming and Oases Cropping Laboratory, Arid Lands Institute of Medenine, Gabes, Tunisia
[3]Faculty of Biotechnology, University of Agronomic Sciences and Veterinary Medicine of Bucharest, 59 Marasti Blvd, District 1, Bucharest, Romania

Corresponding author email: maria-luiza.mircea@usamv.ro

Abstract

Brewery wastewater, a waste of the brewing process, presents significant environmental and operational challenges due to its high organic load, nutrient content, and volume. However, its valorisation offers a promising avenue for sustainable resource recovery, particularly in the food industry. This study explores innovative treatment technologies and circular economy strategies to transform brewery wastewater into valuable resources. Anaerobic digestion and membrane bioreactor systems enable the recovery of clean water for reuse in cleaning and cooling processes while generating biogas as a renewable energy source. Nutrient recovery technologies facilitate the extraction of nitrogen and phosphorus, which can serve as biofertilizers for agricultural use or as growth substrates in food-grade fermentation processes. The integration of brewery wastewater valorisation pathways mitigates environmental impacts while enhancing brewery industry profitability and contributing to food industry innovation. This study underscores the potential of brewery wastewater as a resource, highlighting the importance of technological advancements and interdisciplinary collaboration in achieving sustainable food systems.

Key words: *agriculture, anaerobic fermentation, brewery wastewater, food, organic acids.*

INTRODUCTION

Wastewater treatment serves as solid foundation for technological advancements aimed at reshaping production systems, due to its long-standing global presence and well-established technological background. It is estimated that wastewater contains between 50% and 100% of recoverable lost resources (Puyol et al., 2017). As a result, main factors including economic, environmental, and industrial sectors, are increasingly advocating for the recovery and valorisation of these materials. In this context, the European Union has made significant investments in the bioeconomy, notably through the recent establishment of the Biobased Industries Joint Undertaking, a Research and Innovation program under the Horizon 2020 framework (Deploying the Bioeconomy in the EU: A framework approach for bioeconomy strategy development). Similarly, the United States has emerged as a major proponent of the bioeconomy, particularly with the launch of the National Bioeconomy Blueprint (Frisvold et al., 2021). Beer is currently the fifth most consumed alcoholic beverage globally (kirinholdings.com, 2024), with a widespread network of large-scale production facilities. However, this extensive production is accompanied by significant volumes of wastewater generated by breweries (between 3 and up to 10 L of wastewater, for 1 L of beer (Fillaudeau et al., 2007). During the beer processing, beer undergoes a couple of stages chemical, physico-chemical and biochemical processes: mashing, boiling, and fermentation, stabilisation. In the mashing stage, enzymes convert malt starch into fermentable sugars, primarily maltose and maltotriose (De Schepper et al., 2022), along with non-fermentable sugars such as dextrins. During this enzymatic conversion process, a sweet liquid known as wort is produced, along with a solid by-product called spent grains (Lamberti, L., 2024). After filtration, the wort is transferred to the brewing kettle, where it is boiled together with hops. The brewing industry produces a diverse range of by-products and waste materials such as spent grains, sludge, and wastewater (Figure 1). The brewery wastewater is the effluent generated during the various stages of beer production: cleaning, brewing, fermentation, and packaging. If not managed appropriately, these residues can contribute to environmental pollution due to their high organic load and nutrient content (Pasquet et al., 2024).

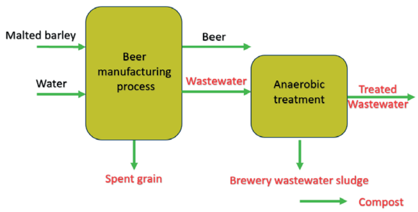

Figure 1. Brewery wastewater treatment
(after Simate et al., 2011)

However, these by-products hold considerable potential for valorisation through various sustainable applications. Brewer's spent grain, the most abundant by-product, is rich in fibre and protein (Naibaho et al., 2024), making it a valuable ingredient in animal feed and functional food formulations. Brewers spent grains and sludge contain bioactive compounds that can be utilized in biotechnology (Chattaraj et al., 2024) and animal feed supplementation (Grigore et al., 2023a, Dumitru et al., 2024). Additionally, spent hops and other organic residues can be harnessed for bioenergy production through anaerobic digestion or fermentation processes (Vasileiadou et al., 2024). Wastewater from brewing operations, which contains significant levels of organic matter (Li et al., 2025) and nutrients, can be treated and repurposed for irrigation or biotechnological processes. The valorisation of by-products generated from the brewing industry to extract bioactive compounds and create novel products represent a highly relevant and current research focus. This approach holds significant importance not only in the context of the food-health relationship but also in terms of environmental sustainability and waste management.

MATERIALS AND METHODS

This review was conducted through a targeted and critical analysis of the current scientific literature addressing the treatment and valorisation of brewery wastewater, with a particular focus on technologies enabling resource recovery in alignment with circular economy principles. A structured search strategy was implemented across major academic databases, including Web of Science, Scopus, PubMed, and ScienceDirect, using combinations of controlled vocabulary and specific terms such as "brewery effluent treatment", "membrane bioreactor systems", "nutrient recovery technologies", and "valorisation of organic compounds from industrial wastewater". The literature selection was limited to peer-reviewed publications in English, published between 2019 and 2024, prioritizing experimental studies, reviews, and case reports that provided data on process efficiency, environmental performance, and applicability to food and agricultural systems. Additional grey literature, including technical reports and regulatory documents, was evaluated for contextual relevance. The collected data were systematically categorized according to the treatment objective, namely water reuse, energy generation, nutrient recovery, and extraction of bioactive compounds, and assessed in terms of operational feasibility, and scalability.

RESULTS AND DISCUSSIONS

Beer industry wastewater

Producing one Liter of beer typically requires between 9 and 10 Liters of water, with roughly 3 to 10 Liters turning into wastewater (Umego et al., 2024). Large-scale breweries or those implementing advanced technologies can reduce water consumption below these levels (using approximately 2.1-3.2 hL of water per 1 hL of beer) (Belhu M., 2022), yet wastewater management remains a significant challenge. The majority of water in breweries is consumed for cleaning and sterilizing equipment.

Table 1. Fundamental steps in wastewater treatment systems

Strategy	Objective	Beer Production	References
Screening	Removal of large particles and debris from the wastewater through mesh filters or screens.	Prevents clogging in subsequent treatment stages and protects equipment.	Ahmed et al., 2021
Sedimentation	Separation of heavier solids from the liquid by gravity, allowing them to settle at the bottom of the tank.	Reduces suspended solids in brewery wastewater, aiding in the clarity of treated water.	Bandh et al., 2025
Air flotation	Uses fine bubbles to lift lighter particles to the surface, where they can be skimmed off.	Helps remove oils, greases, and lighter contaminants in brewery wastewater.	Mukandi et al., 2023
Coagulation	Addition of chemicals (coagulants) to neutralize charges of suspended particles, followed by flocculants to form larger aggregates (flocs).	Enhances the removal of fine particles and suspended solids from beer wastewater.	Carnevale Miino et al., 2025
pH adjustment	Adjusting the pH of the wastewater to ensure optimal conditions for subsequent treatment processes.	Helps to neutralize acidic or alkaline beer wastewater, preparing it for further treatment.	Khumalo et al., 2023
Grit Removal	Removal of heavy, inorganic particles (e.g., sand, gravel) from the wastewater using a grit chamber.	Prevents wear and tear on treatment equipment and helps improve water clarity.	Abubakar et al., 2022
Flotation	Similar to air flotation, but may use a variety of physical processes (e.g., dissolved air flotation) to separate solids from liquids.	Used to separate suspended solids, especially in the presence of oils and fats from brewery wastewater.	Logan et al., 2022
Rotating Biological Contactors	Uses rotating discs or media to provide a surface for microbial growth, aiding in the removal of organic matter.	Primarily used in biological treatment, but may also serve as an initial pre-treatment to reduce organic load in wastewater.	Mizyed et al., 2021
Ultrafiltration	A type of membrane filtration that separates particles, colloids, and some macromolecules from liquids using a semipermeable membrane.	Can be used for finer filtration of brewery wastewater to remove suspended solids, microorganisms, and some organic materials.	Jihill et al., 2024
Chemical Precipitation	Chemical agents are added to wastewater to form insoluble compounds that can be separated by sedimentation.	Used to remove heavy metals or phosphorus from brewery wastewater before biological treatment.	Razzak et al., 2022
Anaerobic Digestion	A biological process where microorganisms break down organic material in the absence of oxygen, often used for high organic load wastewater.	Can be applied as a pre-treatment to reduce organic pollutants and generate biogas from brewery wastewater.	Kumar et al., 2024
Biofilm Reactors	A biological treatment method where microorganisms attach to a surface (biofilm) and treat the wastewater as it flows over them.	Similar to RBCs, used in some beer production wastewater treatment systems to treat organic waste.	Deena et al., 2022
Wetland Treatment	Uses natural or constructed wetlands to treat wastewater by filtering through soil and plants that absorb nutrients and pollutants.	Can be used as an eco-friendly, low-cost method for treating brewery wastewater in some smaller operations.	Hassan et al., 2021
Ozonation	Application of ozone (O_3) to wastewater to break down organic contaminants and disinfect the water.	Helps in disinfection of brewery wastewater and the removal of organic contaminants before discharge or reuse.	Mostashari et al., 2022
Activated Carbon Adsorption	Activated carbon is used to adsorb organic compounds and pollutants, effectively removing contaminants from wastewater.	Often used in conjunction with other treatment methods to remove residual organic compounds from brewery wastewater.	Pauletto et al., 2022

Since water is involved in every stage of the brewing process, wastewater composition varies considerably. Beyond its primary constituents, brewery effluents may contain cleaning agent residues (Łukaszewicz et al., 2024), alkaline and acidic compounds (Pasquet et al., 2023), as well as remnants of raw materials and chemicals used during beer production (Bonato et al., 2022), such as wort, spent grains, hops, yeast, alkaline solutions from polyvinylpolypyrrolidone (PVPP) filtration, and diatomaceous earth (Kahle et al., 2021). Due to its intensive water requirements, the brewing industry generates substantial quantities of wastewater with significant pollutant loads throughout the year. It is important to recognize that the composition and volume of effluents vary across different production stages. For instance, while bottle cleaning contributes significantly to the total volume of wastewater, it accounts for only a small proportion of the overall organic matter released during brewing operations. Common components of brewery wastewater include a total organic of 3 % of sugars, dissolved starch, ethanol, volatile fatty acids, and suspended solids (Simate et al., 2011).

The large quantities of wastewater generated in beer production require environmentally responsible solutions to minimize pollution while complying with purity regulations. This goal can be achieved through various strategies:

a) Optimizing water consumption during production or integrating modern technologies;
b) Repurposing used water for alternative applications;
c) Ensuring proper treatment before discharging it into wastewater systems or the environment.

However, due to financial constraints, some breweries, such smaller or artisanal production breweries, may struggle to implement costly wastewater treatment technologies. Nevertheless, all brewery units are still subject to the same regulatory standards regarding wastewater purity as large-scale operations. As a result, adopting alternative or decentralized treatment solutions may be particularly suitable and beneficial for such facilities. Consequently, alternative approaches have been proposed to make use of brewery wastewater (Olajire A., 2020). For instance, because brewery wastewater is rich in carbon and essential nutrients, it can serve as a valuable medium for cultivating microalgae (Dias et al., 2023). Additionally, its high organic content makes it a suitable nutrient source for hydroponic plant cultivation (Taylor et al., 2018). Hydroponics is a soil-free cultivation method that relies on water and dissolved minerals. Nevertheless, if brewery wastewater is to be used in hydroponic systems, it must first undergo anaerobic pre-treatment (Alayu et al., 2021).

Biological treatment methods rely on microorganisms to break down biodegradable pollutants in wastewater, facilitating processes such as carbonaceous organic matter removal, nitrification, denitrification, and stabilization. Anaerobic and aerobic treatments can also lead to methane production (Tsipis et al., 2023). Biological wastewater treatment is widely considered the most effective approach, as it significantly reduces chemical oxygen demand (COD) and biochemical oxygen demand (BOD), with efficiency rates reaching up to 91% (Lokman et al., 2021). Some biological treatment techniques include activated sludge systems, aerated lagoons, trickling filters, biological contactors, stabilization ponds, anaerobic reactors, and biological contaminant removal (Rezai & Allahkarami, 2021). Membrane technology is primarily used in the brewing industry for beer filtration (Ranjit et al., 2021). Research conducted by Braeken et al. (2004) examined the effectiveness of nanofiltration in treating brewery wastewater. Although nanofiltration is commonly used to produce potable water by eliminating low-molecular-weight organic compounds (around 200 g/mol) and detergent additives, it has limited effectiveness in wastewater treatment (Sewerin et al., 2021).

Wastewater treatment and recovery

Brewery wastewater is generally non-toxic and contains a high concentration of organic matter, making it highly biodegradable (Kanagachandran et al., 2006). Wastewater treatment in the brewing industry typically follows an end-of-pipe strategy. However, due to the high costs and complexity of these methods, many breweries are now focusing on cleaner production techniques to reduce water consumption and seeking more economical treatment alternatives (Amenorfenyo et al., 2019; Khumalo et la., 2023).

The wastewater treatments must undergo few fundamental initial steps (screening for large particles, sedimentation, and air flotation) in many treatment systems, including the beer production industry (Table 1). Screening, a traditional physical method, focuses on eliminating large and floating debris that could potentially hinder the effectiveness of the following treatment processes. Initially, during the physical stage of the beer wastewater treatment, non-dissolvable coarse solids and large particulates are separated. The grit chamber and sedimentation tank are designed to separate floating solid materials. The primary function of the grit chamber is to ensure the settling of larger solid particles (Ahmed et al., 2021), preventing potential blockages in the system. Grit chambers come in different types, such as horizontal flow, vortex flow, and aeration grit chambers, each suited to specific sizes, characteristics, and types of materials being treated (Esfahani et al., 2018). Physical treatment methods are primarily used to remove solid waste from water, such as fiber, sludge, and large particles (Nguyen et al., 2021). The physical methods employed are among the most straightforward and cost-effective, making them accessible to most breweries. However, it is important to note that they do not eliminate dissolved pollutants that can harm ecosystems (Olajire A., 2020). Physical wastewater treatment techniques include screening, shredding, flow equalization, sedimentation, flotation, and granular media filtration (Simate et al., 2011; Ghimpețeanu et al., 2022). Given that nearly half of the total water used in brewing is dedicated to cleaning and disinfection, brewery wastewater naturally contains various chemical substances (like caustic soda, organic acids - as cleaning agents, disinfectants, detergent).

Like physical treatments, chemical processes are relatively simple to apply but come with significantly higher costs, making them less feasible for smaller breweries (Amenorfenyo et al., 2019). For environmental safely, the remove the wastewater chemical contaminants, breweries employ chemical treatment techniques that involve specific chemical reactions. Coagulation, flocculation, and pH adjustments help eliminate toxic residues and colloidal impurities (Durkin et al., 2024).

Chemical oxidation has emerged as a promising technology that utilizes chemical oxidants to transform pollutants into non-harmful and manageable forms. Chemical oxygen demand (COD) serves as a key parameter in this treatment method, and typically, wastewater with low COD levels is treated using this approach (Marcinowski et al., 2020). Thus, chemical oxidation can effectively break down contaminants, reducing their concentration in wastewater. During this process, oxidants are employed to remove pollutants, resulting in the formation of harmless by-products such as water and carbon dioxide (Kao et al., 2020).

Beer wastewater application in biotechnology

Recent studies have increasingly emphasized the potential of brewery wastewater (BWW) as a cost-effective substrate for cultivating oleaginous microorganisms, particularly in symbiotic or co-culture systems, to produce high-value biomolecules such as lipids and carotenoids. Oleaginous yeasts and microalgae not only facilitate efficient wastewater remediation but also contribute to the circular bioeconomy by simultaneously synthesizing valuable compounds such as lipids, which can be used in biofuels or animal nutrition (Dias et al., 2022), and carotenoids with antioxidant and nutraceutical properties (Grigore et al., 2023a, Grigore et al., 2023b).

Recent research (Dias et al., 2022; Lu et al., 2023) has explored various cultivation strategies involving primary (generated directly from the beer producing operations: wort production, fermentation, and filtration; undergoes throughout solids wastes removal) and secondary brewery wastewater (resulted for the cooling and cleaning processes, undergoes biological treatments), either separately or in combination, with and without nutrient supplementation, to optimize microbial growth and metabolite yield. The efforts in recirculating the BWW align with broader global trends seeking sustainable alternatives to conventional resources. Moreover, the rising demand for sustainable protein sources driven by rapid population growth, food security challenges, and the environmental burden of traditional agriculture has accelerated interest in microbial protein (single-cell protein, SCP).

SCP refers to the protein-rich biomass produced by microorganisms such as yeasts, algae, fungi, and bacteria, which has shown promise for inclusion in animal feed, aquaculture diets, and even human consumption (Yap et al., 2022; He et al., 2022; Su et al., 2022). These microorganisms are capable of bio converting low-cost substrates including industrial and agro-industrial wastewaters into high-quality, protein biomass, contributing significantly to both resource valorisation and environmental sustainability (Table 2) (Wang et al., 2022).

Table 2. Beer wastewater application in biotechnology

Production	Target microorganism	End-products outcomes	Advantages of BWW	References
Lipid Production	Oleaginous yeasts microalgae	Biodiesel, nutritional lipids	Low-cost carbon source; simultaneous wastewater remediation	Dias et al., 2023
Carotenoid Synthesis	*Rhodotorula* sp., *Blakeslea trispora*	β-carotene, astaxanthin, and other antioxidant pigments	Nutraceutical and functional food potential; supports microbial pigment biosynthesis	Sharma et al., 2023
Single-Cell Protein	*Saccharomyces cerevisiae* *Chlorella vulgaris*	High-protein biomass for animal feed, aquaculture, or human supplements	Sustainable protein source; reduces reliance on land and freshwater resources	Wang et al., 2022
Enzyme	*Aspergillus niger* *Trichoderma reesei*	Amylases, proteases, cellulases	BWW nutrients support enzyme-inducing metabolic pathways	Jangra et al., 2023
Organic Acid	*Lactobacillus* spp. *Clostridium* spp.	Lactic acid, acetic acid, succinic acid	Useful in food preservation, biodegradable plastics, and green solvents	Wu et al., 2023

Altogether, current finding underscores the high potential of brewery wastewater as a platform for generating novel lipid and protein sources (Dias et al., 2022), while simultaneously reducing environmental impact and promoting circular bioeconomy principles.

Beer wastewater application in agriculture

The global pursuit of sustainable water resources in agriculture has accelerated interest in unconventional alternatives such as treated industrial effluents, with BWW emerging as a promising candidate due to its high organic load and nutrient-rich profile. Given its composition, often containing nitrogen, phosphorus, potassium, and trace micronutrients, BWW can support plant growth while simultaneously addressing water scarcity and waste disposal challenges. Notably, studies have shown that the implementation of crop rotation to mitigate micronutrient depletion did not lead to significant differences in plant growth, indicating that short-term cultivation using BWW may not pose an immediate risk of micronutrient deficiency in soils (Gorfie et al., 2022). Experimental trials (Salian et al., 2018) using a 50:50 mix of BWW and freshwater over five-day germination periods have demonstrated positive effects on seed germination and early growth in crops such as chickpea, corn, and pigeon pea. Similarly, other research supports the use of treated wastewater in agriculture, showing no significant adverse effects on crop yield or quality, with crops like sweet corn and silage maize identified as especially suitable for such irrigation practices (Mok et al., 2014). However, long-term application must be approached with caution, as the accumulation of salts and other residual compounds in soil could impair its structure and fertility, making regular soil monitoring essential to avoid salinity-related issues (Muyen et al., 2011). In the broader context, mounting concerns over water scarcity (Leijnse et al., 2024), declining soil health, and increasing environmental pollution (Rathod et al., 2024) exacerbated by rapid urban expansion, underscore the urgency of integrated wastewater management strategies that align with environmental and agricultural sustainability goals. Traditional wastewater treatment models, focused solely on pollutant removal, must evolve into resource recovery-oriented systems that facilitate the reclamation of nutrients for food production and ecosystem restoration. In this regard, BWW stands out as a readily available and underutilized resource for agricultural irrigation and nutrient cycling, particularly for recovering plant-essential macronutrients such as nitrogen and phosphorus (Carnevale Miino et al., 2025). Moreover, to reinforce economic circularity and sustainable brewery practices, recent studies (Voss et al., 2024; Cichocki et al., 2025) propose innovative nutrient recovery models from BWW, enabling the production of organic liquid fertilizers suitable for hydroponic systems. This approach not only addresses environmental and economic pressures on the brewing industry but also aligns with growing consumer demand for eco-friendly, traceable agricultural inputs.

CONCLUSIONS

BWW traditionally is viewed as an environmental liability, is now emerging as a valuable resource in the context of sustainable development and circular economy principles. This manuscript highlights the multifaceted potential of BWW, emphasizing its application across water reuse, renewable energy generation, biotechnology, and agriculture. In biotechnology, BWW could serve as a low-cost substrate for cultivating oleaginous microorganisms and producing single-cell protein, lipids, and carotenoids biomolecules with growing demand in the food, feed, and nutraceutical sectors. In agriculture, short-term studies have shown that BWW, when appropriately treated, supports crop development without compromising soil health or plant quality, provided that salinity and contaminant levels are carefully monitored. Overall, the valorisation of brewery wastewater presents an integrative approach to environmental management, resource efficiency, and industrial innovation. Realizing its full potential, however, requires coordinated efforts involving technological advancement, policy support, and cross-sector collaboration. By shifting from linear waste disposal models to resource recovery systems, breweries can not only reduce their ecological footprint but also contribute to broader global goals related to food security, water conservation, and sustainable production systems.

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