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Life cycle assessment of innovative methods for treating wastewater and solid wastes: a case study focusing on their application within the brewing sector

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The brewing sector is known for its high energy consumption, significant water usage, and the generation of substantial solid and liquid waste. Therefore, effective treatment methods for these wastes have been explored to treat and either recycle water within the industry or proceed to safe aquatic discharge, while repurposing solid waste for energy production and valuable products. This study aims to assess the overall environmental sustainability of solid waste valorization and wastewater treatment in a brewery through Life Cycle Assessment (LCA). The evaluation involved comparing the total environmental impact of a typical brewing industry utilizing conventional waste management methods (base case scenario) with two alternative approaches employing appropriate waste treatment and valorization processes. In scenario A, waste management employed anaerobic digestion coupled with a cogeneration unit, aeration treatment, and membrane filtration treatment. Meanwhile, Scenario B utilized gasification, screening, membrane bioreactors and UV treatment as treatment techniques. As anticipated, the LCA study revealed that both Scenarios A and B exhibited significantly improved environmental footprints across all studied indicators compared to the base case scenario, with reductions in the greenhouse gas emissions reaching up to 25.90% and 45.68% for Scenarios A and B, respectively. The findings from this case study underscore the potential for the brewing industry to efficiently generate energy and markedly improve its environmental footprint by integrating appropriate waste treatment methods. This contribution to environmental safety and sustainability emphasizes the significance of adopting suitable techniques within the industry.

Sustainability spotlight

This study illustrates the brewing sector's sustainable progression with tangible evidence of reduced environmental impact. It exemplifies advancements in waste management by showcasing reductions in GHG emissions, energy generation from waste, and enhanced environmental footprints compared to conventional practices. Aligning with the UN's Sustainable Development Goals, this work contributes notably to multiple goals. It addresses Goal 6 (Clean Water and Sanitation) by exploring effective wastewater treatment methods and Goal 7 (Affordable and Clean Energy) by demonstrating waste valorization's energy generation. Moreover, it aligns with Goal 13 (Climate Action) and serves as a pivotal example of sustainable practices in an industry traditionally associated with high resource consumption and waste generation, embodying the essence of multiple Sustainable Development Goals.

Introduction

The brewing sector holds the distinction of being the most ancient and universally acclaimed beverage industry on a global scale.[1] The main beer ingredients are malt that can come from different cereals (*i.e.* barley, wheat, and oats), water, hops and yeasts. The approach of the different cereals is employed either for economic purposes, as seen with corn, or to create beers with unique flavor and aroma, as exemplified by wheat, which is essential for specific styles of beers.[1–3]

Beer production is a combination of malting and brewing processes. More specifically, the malting process relies on water for steeping and energy primarily for germination, kilning, and storage. The energy needs can vary based on the scale of the malting operation, the efficiency of equipment and processes, and the type of energy sources used. Modern malting facilities aim to optimize both water and energy usage to reduce environmental impact and operational costs. As for the brewing process, it involves water for mashing, lautering, cooling, and cleaning, and energy is mainly required for heating during

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mashing and boiling, cooling, and packaging.[3] The specific water and energy demands can vary depending on the brewery's size, technology, and the type of beer being produced, with modern breweries focusing on sustainability and efficiency to reduce resource consumption along with their environmental impact. Thus, beer production is a resource-intensive process that consumes substantial quantities of grains, water, and energy, resulting in the generation of significant amounts of solid wastes and wastewater. Various methods have been employed to address these waste products, with the goal of purifying the wastewater and harnessing the potential energy within the solid waste to promote the recycling of the generated energy within the industry.

Among the various methods available for treating and making better use of beer processing by-products, the following techniques are considered highly suitable due to their effectiveness in both wastewater treatment and the generation of renewable energy from waste materials: membrane bioreactors, aeration treatment, ultraviolet (UV) treatment, anaerobic digestion, and gasification. Aeration treatment involves the introduction of air into wastewater, enabling the biodegradation of organic compounds and leading to water decontamination.[4] Simultaneously, membrane treatment aids in the removal of suspended particles and microorganisms from the treated water.[5] Anaerobic digestion, a process for wet solid waste, efficiently breaks down organic matter through microorganisms, ultimately converting it into biogas.[6] Subsequently, the generated biogas can be harnessed in a biogas cogeneration unit to produce renewable electricity and heat.[7] A membrane bioreactor is an advanced approach for wastewater treatment, combining a biological process (aeration treatment) with membrane filtration. This method involves a bioreactor tank where biomass is broken down, followed by membrane filtration to eliminate microorganisms from the treated water.[1] UV treatment is an efficient technique for disinfecting treated water by subjecting it to ultraviolet light, which effectively eliminates harmful pathogens like bacteria and viruses.[8] Finally, gasification of solid wastes involves converting them into combustible gases, mainly in the form of hydrogen, through a high-temperature process in the absence of oxygen.[9]

The assessment of environmental impacts in product systems is facilitated using Life Cycle Assessment (LCA), a valuable framework that considers inputs, outputs, and potential environmental effects throughout the entire life cycle of a product system.[10,11] LCA's primary purpose is to identify key environmental hotspots during various production stages and offer recommendations for enhancing the overall production process with a focus on environmental sustainability.[12]

The main purpose of this study is to investigate whether the processing of wastewater and solid wastes within the boundaries of a brewery can exhibit a positive impact on its environmental footprint in the brewing industry. The primary objective of this study is to assess the sustainability from an environmental aspect of a beer industry adopting advanced wastewater treatment methods; aeration and membrane treatment for Scenario A and membrane bioreactors as well as UV treatment for Scenario B. Moreover, for the valorization of solid wastes, anaerobic digestion coupled with CHP was studied for Scenario A and gasification for the latter scenario. Subsequently, the two different scenarios were directly compared with current practices regarding the disposal of wastewater (transportation to municipal wastewater treatment plants) and solid wastes (biodegradable waste in landfills) in most breweries, utilizing LCA as the evaluation tool. To sum up, the main scope of the present study is to assess the environmental sustainability of incorporating novel methods in the valorization of solid wastes and the treatment of wastewater that are generated in the brewing industry *via* performing an LCA analysis.

Methodology

An LCA study was conducted in accordance with the guidelines put forth in the ISO 14040 series (specifically, ISO 14040:2006 and ISO 14044:2006). The ReCiPe 2016 (Hierarchist) method was chosen for conducting the impact assessment.[12] Its primary purpose is to convert life cycle inventory data into a concise set of environmental impact scores using characterization factors.[12] The software tool utilized for this study was GABI ts software (version 10.6.2.9, Sphera Solutions 95 GmbH, Echterdingen, Stuttgard, Germany).

Aim & scope

The primary objective of the present LCA study was to analyze the environmental impact of implementing various wastewater and solid waste treatment methods within a typical brewing industry. Initially, the study evaluated the environmental footprint of a standard brewing operation using data sourced from published studies that were validated and updated following communication with a local brewery. Subsequently, two alternative scenarios were explored, which have incorporated different techniques for treating wastewater and utilizing waste within the studied system.

The study centered on a conventional brewing operation as the baseline case, focusing on the production of beer as the final product. The various processes involved in brewing, illustrated in Fig. 1, include grinding, mashing, boiling, fermentation, conditioning, filtration and finally the packaging. Each stage was analyzed to understand its environmental impact and resource utilization within the broader context of the brewing industry.

Regarding the base case scenario that is depicted in Fig. 1, the produced wastewater is conveyed to and treated at a municipal wastewater treatment facility, while solid waste is simply disposed of in landfills; thus the brewing industry adopts a passive approach. This traditional practice reflects a historical norm where industries typically remained detached from the active treatment and reutilization of their wastes.

In Scenario A, wastewater and solid wastes are treated on site within the boundaries of the industry (Fig. 2). Specifically, wastewater is first subjected to aeration treatment and subsequently filtered through a membrane unit to obtain clean water. Solid wastes undergo treatment in an anaerobic digester, where the resulting biogas, after removing CO_2 to enhance methane

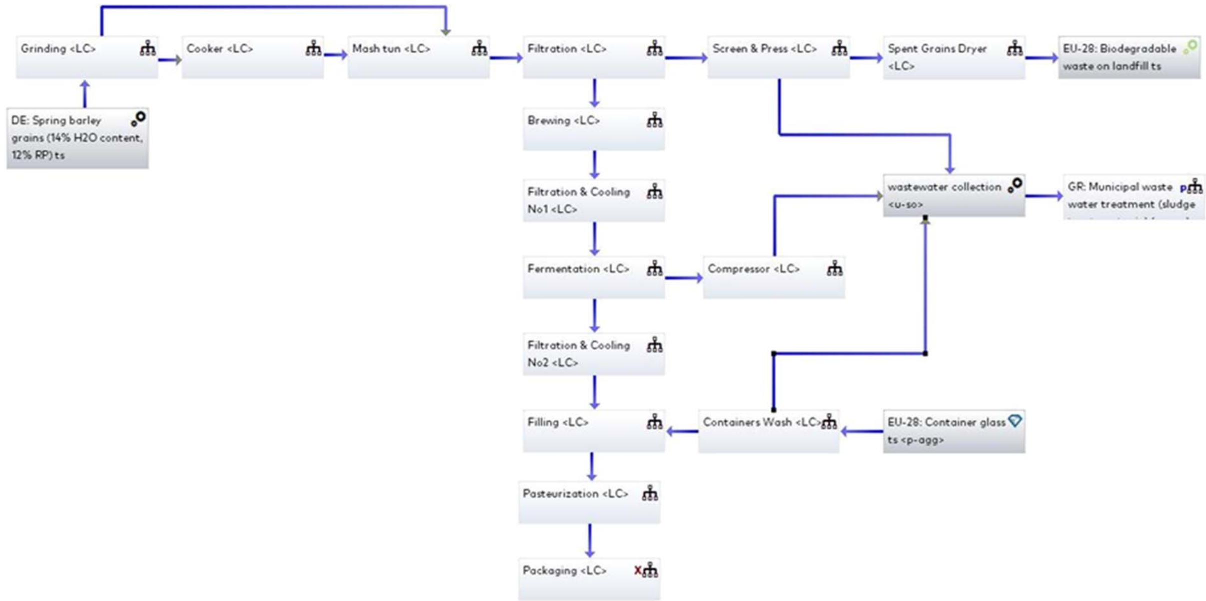

Fig. 1 Production processes and wastewater and solid waste treatment in the base case scenario.

concentration, is utilized for electricity and heat generation through cogeneration.[13]

Scenario B (Fig. 3) includes several meticulous stages for the treatment of wastewater and the valorization of solid wastes. Initially, wastewater is screened to remove large solids, and then enters a membrane bioreactor followed by a subsequent exposure to UV light. The resulting water achieves a quality level suitable for either recycling within the industry to curtail fresh water consumption or safe discharge into aquatic ecosystems. Solid waste valorization is accomplished utilizing gasification, a process in which the solid wastes (mainly spent grains) are converted into hydrogen, which can be used for the production of electricity and thermal energy. In Scenarios A and B, the production of thermal energy and electricity is represented as thermal and electricity credits, respectively. These credits typically contribute positively to the environmental footprint of

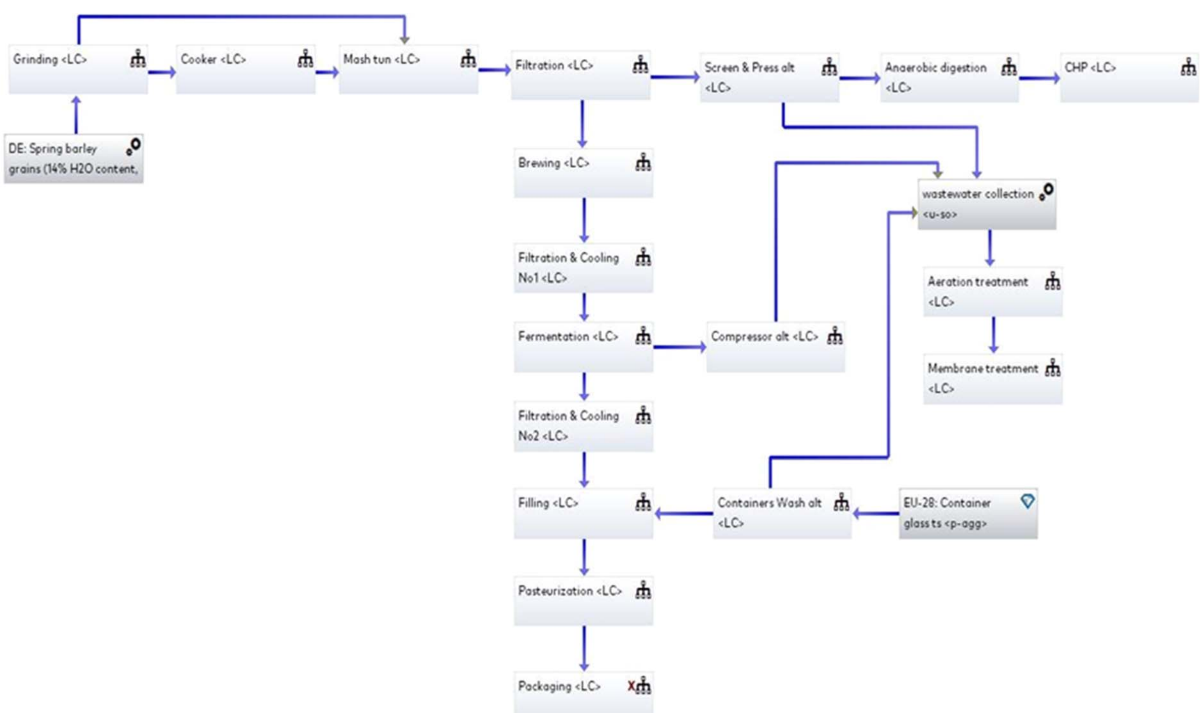

Fig. 2 Production processes and wastewater and solid waste treatment in Scenario A.

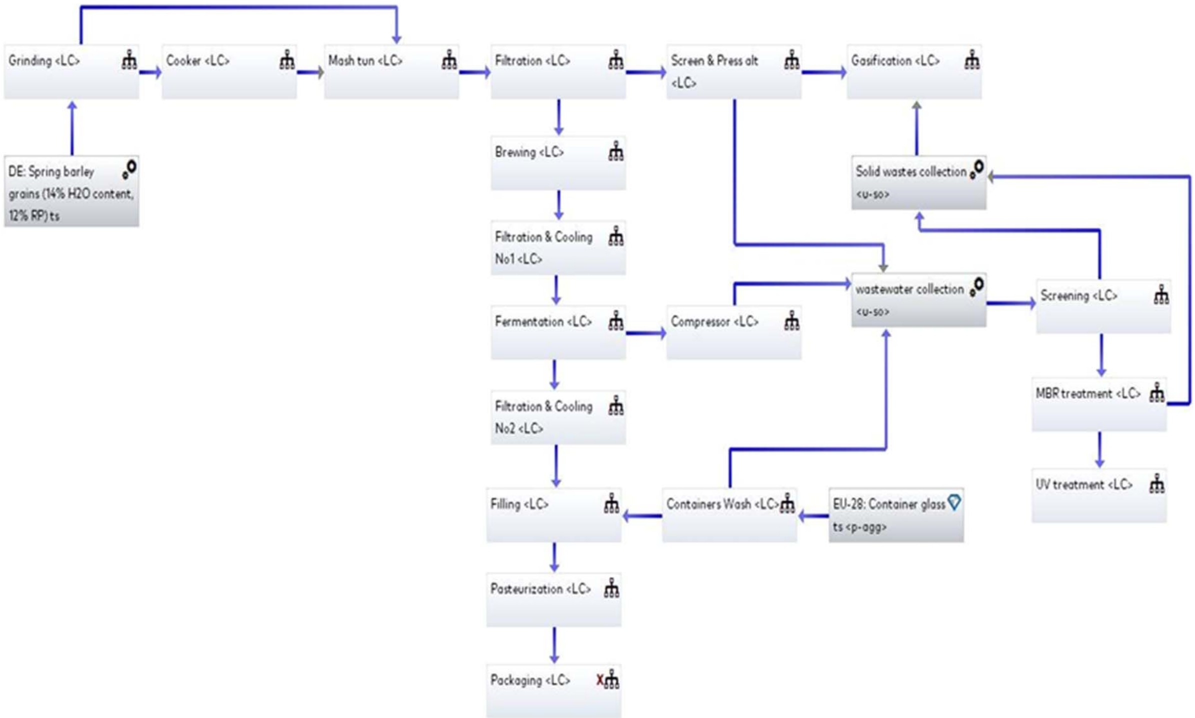

Fig. 3 Production processes and wastewater and solid waste treatment in Scenario B.

both scenarios as they stem from the valorization of waste, rather than relying on the traditional combustion of fossil fuels for energy generation.

Functional unit

For this study, the chosen measurement standard was the production of 330 mL of packaged beer, using glass containers for all studied scenarios.

System boundaries

In the evaluation of the environmental impact of packaged beer production within a typical brewing industry, the system's boundaries are set from 'gate-to-gate'. This encompasses all processes from the grinding to the packaging of the final product. Additionally, for the two examined scenarios (Scenarios A and B), the system boundaries remain 'gate-to-gate', encompassing all the production processes along with the examined wastewater and solid waste treatment. However, it's important to note that the transportation of raw materials, including spring barley, and the final products lies outside these defined system boundaries. The aforementioned system boundaries are applied to all studied scenarios.

Data requirements

The study utilized information sourced from accessible references as well as the GABI professional and Ecoinvent databases, specifically referencing the geographical scope of the European Union 28 (EU-28). All referenced studies and data, along with the used scientific databases, encompass information from the past five years.

Assumptions & limitations

The data employed in the present study, sourced primarily from existing literature, align with a set of inherent assumptions and limitations that need to be considered to understand the scope and robustness of the conclusions.

A significant assumption is the homogeneity and reliability of the data across different literature sources. One major assumption is that these sources provide consistent and representative information applicable to our scenarios, despite potential variations in data collection methods and reporting standards. This assumption extends to the operational conditions and efficiencies across different breweries, presuming them to be similar to those described in the literature.[14]

Another critical assumption is the uniform impact of uncertainty across all scenarios. This implies that any inconsistencies or variations in data quality do not bias one scenario over another, thereby maintaining a level playing field. Additionally, static environmental conditions are assumed, which may not accurately reflect real-world variances such as local climate differences and resource availability.

Technological consistency is another assumption, where it is hypothesized that the technology and processes used in waste treatment and beer production are in line with those documented in the literature. This does not account for advancements or regional differences in process efficiency, which could impact the study's outcomes.

However, these assumptions bring several limitations. The reliance on literature data may not fully capture the diversity and complexity of real-world situations, leading to potential inaccuracies in estimating environmental footprints. Geographical and temporal variations, such as regional

Table 1 Life Cycle Inventory (LCI) of a conventional brewing industry (based on Brown *et al.*[16] and adjusted to current data *via* communication with a brewery located in the Attica area)

Process	Flow	In/out	Unit	Value
Grinding	Spring barley	In	kg	0.0635
	Electricity	In	MJ	0.0145
	Graded malt	Out	kg	0.0571
	Spring barley	Out	kg	0.0064
Cooker	Water	In	kg	0.0971
	Thermal energy	In	MJ	0.0241
	Steam	In	kg	0.0181
	Spring barley	In	kg	0.0064
	Spring barley	Out	kg	0.122
Mash tun	Water	In	kg	0.213
	Spring barley	In	kg	0.122
	Graded malt	In	kg	0.0572
	Thermal energy	In	MJ	0.0508
	Steam	In	kg	0.0227
	Spring barley	Out	kg	0.392
Filtration	Spring barley	In	kg	0.392
	Water	In	kg	0.136
	Thermal energy	In	MJ	0.0324
	Electricity	In	MJ	0.0089
	Spent grains	Out	kg	0.0576
	Spring barley	Out	kg	0.47
Screening & pressing	Spent grains	In	kg	0.0576
	Electricity	In	MJ	0.0089
	Spent grains	Out	kg	0.0191
	Wastewater 1	Out	kg	0.0386
Spent grain dryer	Thermal energy	In	MJ	0.317
	Spent grains	In	kg	0.0191
	Electricity	In	MJ	0.0053
	Spent grains to a landfill	Out	kg	0.0018
Brewing	Spring barley	In	kg	0.47
	Steam	In	kg	0.0408
	Spring barley	Out	kg	0.463
Filtration and cooling 1	Spring barley	In	kg	0.463
	Electricity	In	MJ	0.0604
	Spring barley	Out	kg	0.455
Fermentation	Spring barley	In	kg	0.455
	Yeast	In	kg	0.0109
	Electricity	In	MJ	0.004
	Beer	Out	kg	0.438
	Carbon dioxide	Out	kg	0.0218
Compressor	Water	In	kg	0.181
	Carbon dioxide	In	kg	0.0218
	Electricity	In	MJ	0.0093
	Wastewater 2	Out	kg	0.181
	Carbon dioxide	Out	kg	0.0218
Filtration and cooling 2	Beer	In	kg	0.438
	Electricity	In	MJ	0.0084
	Refrigerant	In	kg	0.002
	Beer	Out	kg	0.438
Filling	Beer	In	kg	0.438
	Container glass	In	kg	0.0136
	Electricity	In	MJ	0.0053
	Beer	Out	kg	0.454
Container wash	Water	In	kg	0.181
	Thermal energy	In	MJ	0.043
	Container glass	In	kg	0.0136
	Container glass	Out	kg	0.0136
	Wastewater 3	Out	kg	0.181
Pasteurization	Water	In	kg	1.13
	Beer	In	kg	0.454
	Thermal energy	In	MJ	0.27
	Beer	Out	kg	0.454

Table 1 (*Contd.*)

Process	Flow	In/out	Unit	Value
Packaging	Beer	In	kg	0.454
	Electricity	In	MJ	0.0137
	Beer	Out	kg	0.454
Wastewater collection	Wastewater 1	In	kg	0.0386
	Wastewater 2	In	kg	0.181
	Wastewater 3	In	kg	0.181
	Wastewater to a municipal wastewater treatment plant	Out	kg	0.401

Table 2 Life Cycle Inventory (LCI) of Scenario A

Process	Flow	In/out	Unit	Value
Anaerobic digestion[15]	Spring barley	In	kg	0.042
	Thermal energy	In	MJ	8.56×10^{-5}
	Electricity	In	MJ	1.37×10^{-5}
	Biogas	Out	kg	0.00809
CHP[16,17]	Biogas	In	kg	0.0478
	Electricity	Out	MJ	0.42
	Thermal energy	Out	MJ	0.48
Aeration treatment[18]	Wastewater	In	kg	0.882
	Electricity	In	MJ	0.00254
	Wastewater	Out	kg	0.882
Membrane treatment[19]	Wastewater	In	kg	0.882
	Electricity	In	MJ	0.00196
	Clean water	Out	kg	0.882

differences in environmental regulations and changes in technology over time, are not accounted for, which could affect the generalizability of the obtained results.

The study also simplifies complex environmental processes and interactions, potentially overlooking certain indirect or long-term impacts. Moreover, it may not cover all environmental impact categories comprehensively, focusing primarily on those directly related to wastewater and solid waste treatment.

To understand the robustness of the conclusions, a sensitivity analysis was conducted by varying key parameters within realistic ranges.

Table 3 Life Cycle Inventory (LCI) of Scenario B

Process	Flow	In/out	Unit	Value
Solid waste collection	Sludge	In	kg	0.00105
	Solid waste	In	kg	0.001
	Solids	Out	kg	0.00205
Gasification[9]	Spent grains	In	kg	0.0191
	Solids	In	kg	0.00205
	Electricity	Out	MJ	0.0987
	Solid waste in a landfill	Out	kg	2.45×10^{-5}
Screening[20]	Wastewater	In	kg	0.883
	Electricity	In	MJ	4.5×10^{-6}
	Wastewater	Out	kg	0.881
	Solids	Out	kg	0.0022
Membrane bioreactor[21]	Wastewater	In	kg	0.881
	Electricity	In	MJ	0.0044
	Wastewater	Out	kg	0.879
	Sludge	Out	kg	0.0023
UV treatment[22]	Wastewater	In	kg	0.879
	Electricity	In	MJ	0.000209
	Clean water	Out	kg	0.879

Life cycle inventory

The Life Cycle Inventory (LCI) links processes with quantitative data. Table 1 details input and output data for all processes within the brewery, as depicted in Fig. 1. While initially referencing literature sources for data collection and inventory establishment, modifications were made after verification through communication with a brewing industry based in the Attica area of Greece. Environmental data were sourced from the GABI professional (8007 db version 2022) and Ecoinvent (Ecoinvent 3.8) databases.

Tables 2 and 3 outline the input and output specifics for each process within the various scenarios, as depicted in Fig. 2 and 3.

Uncertainty analysis

The main processes that may exhibit a strong influence towards the attained results from the two alternative scenarios (A and B) include anaerobic digestion, aeration treatment, membrane treatment, gasification, membrane bioreactors and UV treatment. However, from the life cycle inventory, it is evident that the energy consumption associated with the wastewater treatment methods is relatively low; thus, any variations in these values will not affect the obtained results. However, the efficiency of the anaerobic digester in biogas production and of the gasification process in hydrogen production may significantly affect the environmental footprint of the alternative scenarios. Thus, a sensitivity analysis was carried out regarding the effectiveness of anaerobic digestion and gasification. More specifically, two additional values for biogas production were studied (0.25 and 0.40 m^3 CH_4 per kg VS) based on the literature, while the median of these values was selected for the initial study of Scenario A.[23,24] Regarding Scenario B, two additional values for hydrogen production were evaluated (30 and 70 g H_2 per kg BSG) based on the literature, while the median of these values was selected for the initial evaluation of Scenario B.[25,26]

Results and discussion

Fig. 4 illustrates both the overall environmental impact of the standard brewing industry and the specific environmental effects associated with each individual process. The brewing industry exhibits substantial energy consumption and generates significant volumes of solid waste and wastewater, leading to notable environmental impacts across various categories. Specifically, in terms of greenhouse gas emissions, fossil depletion, and human toxicity (related to cancer), the industry reflects values of 0.139 kg CO_2 eq., 3.89×10^{-2} kg oil eq., and 7.91×10^{-5} kg 1,4-DB eq., respectively. Moreover, it's crucial to note that spring barley, a key ingredient in beer production, contributes significantly to environmental footprints, particularly impacting freshwater ecotoxicity, eutrophication, and marine ecotoxicity. Despite its pivotal role, altering its utilization poses a challenge. Therefore, efforts to mitigate environmental impact should primarily focus on optimizing wastewater and solid waste treatment processes. However, to improve the environmental footprint during the cultivation of barley, precision farming techniques to optimize resource use, and reduce water, fertilizer, and pesticide consumption can be implemented. Additionally, adopting crop rotation and cover cropping practices can enhance soil health and biodiversity, minimizing the need for chemical inputs and reducing greenhouse gas emissions. This underscores the potential for enhancing environmental performance through the valorization of solid waste and wastewater treatment within the brewery's boundaries. Additionally, it must be noted that the obtained results regarding the carbon footprint of the 330 mL packaged beer are slightly lower compared to that in other research studies. More specifically, the typical carbon footprint of a 330 mL packaged beer in glass containers ranges between 0.278 and 0.364 kg CO_2 eq.[27,28] However, this can be attributed to not including the transportation of the raw materials to the brewery facilities. Moreover, in the present study the environmental footprint of only the spent grains is included and not the one of the yeast and hops, which also exhibit a large environmental footprint,[29,30] but are added in lower quantities during the production processes. Additionally, the carbon footprint of a 330 mL beer, especially in relation to its packaging, has been extensively analyzed in various scientific studies. Packaging is identified as the most significant contributor to the beer's carbon footprint, accounting for about 40% of total emissions. For example, single-use glass bottles and aluminum cans have a higher carbon footprint compared to steel kegs or reusable bottles. The greenhouse gas emissions for beer packaged in single-use glass bottles are approximately 0.45 kg CO_2 equivalent per liter. In contrast, beer packaged in returnable stainless-steel kegs can have emissions as low as 0.05 kg CO_2 equivalent per liter due to their high reuse rate and recyclability, which can further explain the slightly lower results of the present work.[31]

However, the primary aim of the present study was to validate the environmental advantages of the proposed waste treatment methods against traditional wastewater and solid waste treatment. By focusing on these specific stages, all efforts were concentrated on the critical areas, ensuring a thorough and detailed examination. Including additional aspects such as transportation and specific ingredients would have broadened the study's scope, potentially diluting the focus and making it challenging to draw clear conclusions about the waste treatment methods themselves. Moreover, reliable and comprehensive data on the transportation of raw materials and the detailed environmental impacts of yeasts and hops can be difficult to obtain. Transportation data vary widely depending on distances traveled, modes of transport used, and fuel consumption. Similarly, the environmental impacts of cultivating yeasts and hops are influenced by factors such as local agricultural practices, climate conditions, and farming methods. This variability and potential lack of consistent, high-quality data would introduce significant uncertainties into our analysis, complicating the accuracy and reliability of the results. In summary, while including the transportation of raw materials and the incorporation of yeasts and hops would provide a more comprehensive view of the environmental footprint, it was not feasible in the present study due to the need to maintain focus, the challenges in obtaining reliable data, and the methodological constraints involved.

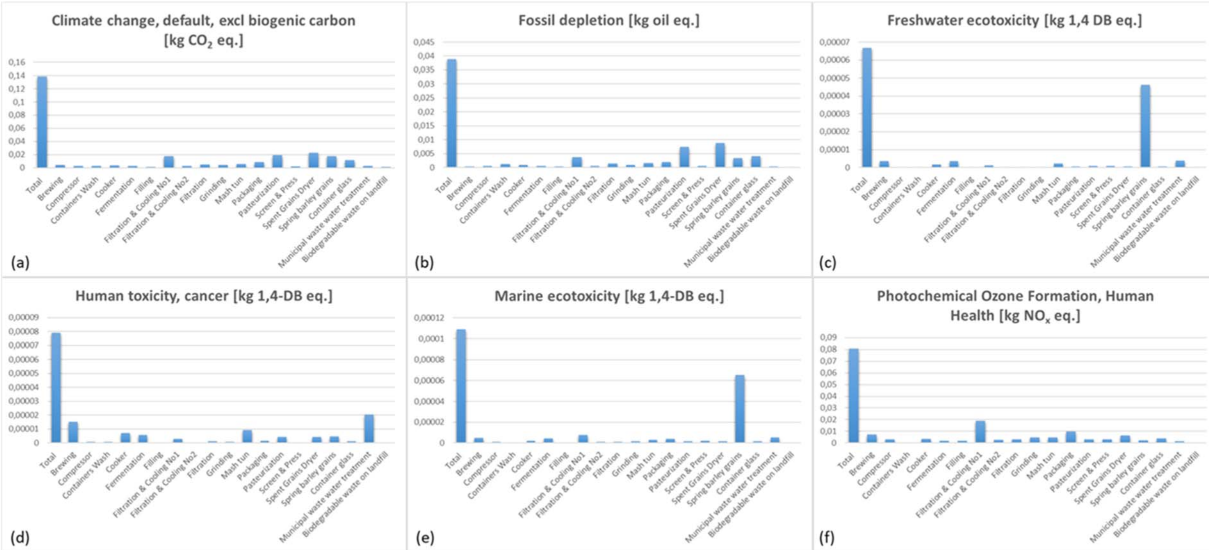

Fig. 4 Environmental effect of the base case scenario in the brewing industry on (a) climate change, default, excl biogenic carbon (kg CO_2 eq.), (b) fossil depletion (kg oil eq.), (c) freshwater ecotoxicity (kg 1,4-DB eq.), (d) human toxicity, cancer (kg 1,4-DB eq.), (e) marine ecotoxicity (kg 1,4-DB eq.), and (f) photochemical ozone formation, human health (kg NO_x eq.).

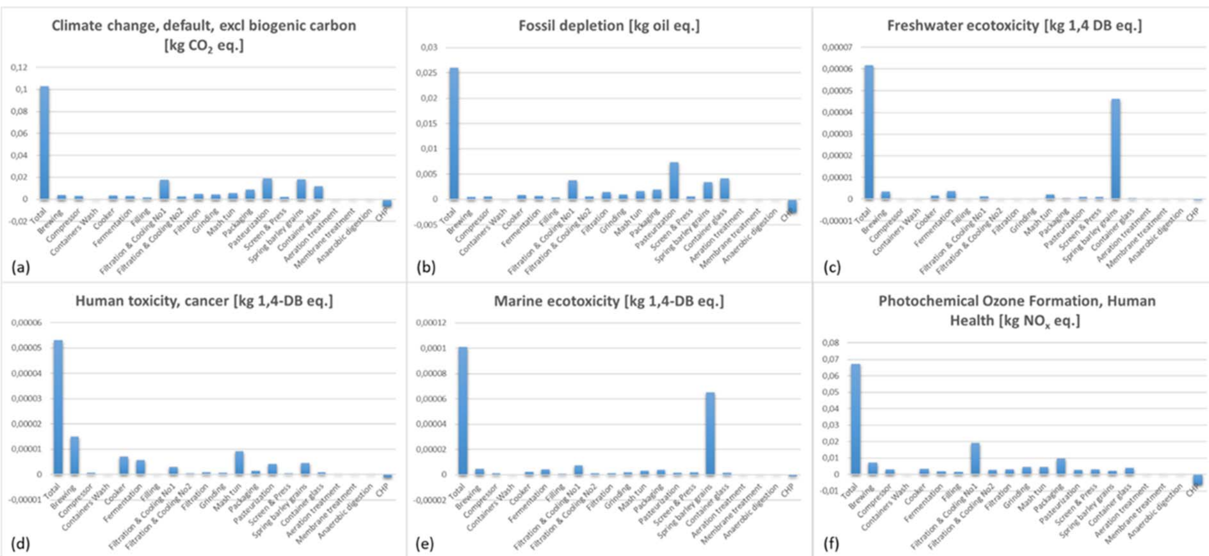

Fig. 5 Environmental effect of Scenario A in the brewing industry on (a) climate change, default, excl biogenic carbon (kg CO_2 eq.), (b) fossil depletion (kg oil eq.), (c) freshwater ecotoxicity (kg 1,4-DB eq.), (d) human toxicity, cancer (kg 1,4-DB eq.), (e) marine ecotoxicity (kg 1,4-DB eq.), and (f) photochemical ozone formation, human health (kg NO_x eq.).

Thus, two different scenarios were studied within the industrial boundaries using the same assumptions as the base case scenario to address this, with the obtained results being presented in Fig. 5 and 6. According to the obtained results, the two studied scenarios that focus on the treatment of wastewater and solid waste within the brewery, employing suitable methods, significantly improve the environmental impact of the studied case. Purifying wastewater efficiently and safely disposing of it in the aquatic environment notably reduce the marine and freshwater ecotoxicity in both Scenarios A (involving aeration treatment and membrane filtration) and B (involving screening, MBR and UV treatment).[32] Additionally, in both studied scenarios a decrease in the greenhouse gas emissions (25.90% and 45.68% for Scenarios A and B, respectively) and in human toxicity regarding cancer (32.87% and 38.18% for Scenarios A and B, respectively) is attained due to the valorization of solid wastes and the production of renewable energy that can substitute the use of conventional fossil fuels. The aforementioned observation can also explain the significant decrease in the studied category of fossil fuels exhibited in both studied scenarios (33.16% and 45.50% for Scenarios A and B, respectively). Finally, Scenarios A and B also achieved an improvement

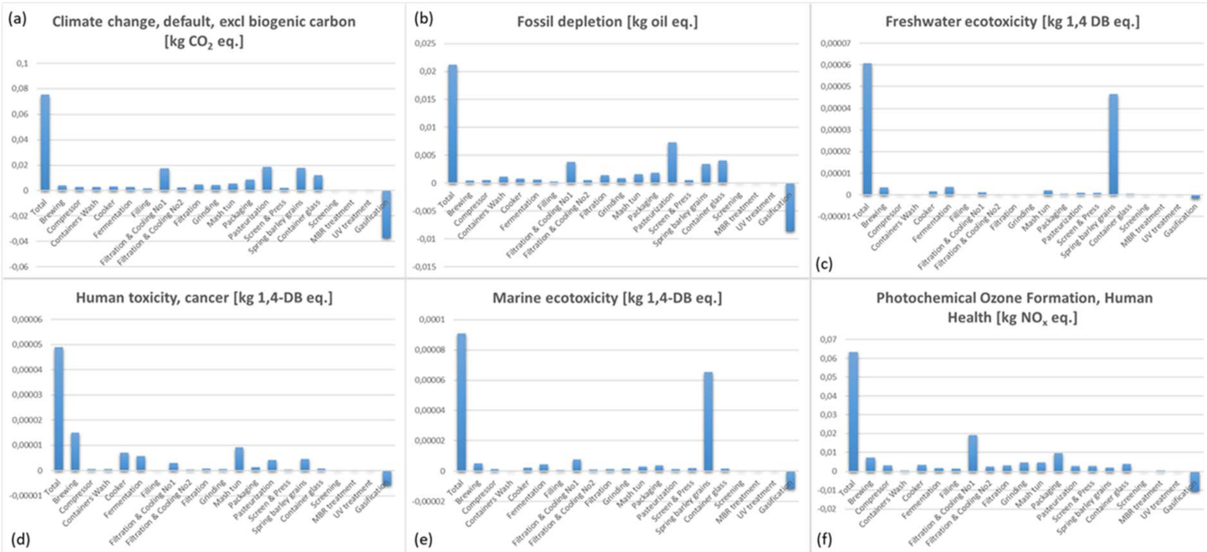

Fig. 6 Environmental effect of Scenario A in the brewing industry on (a) climate change, default, excl biogenic carbon (kg CO_2 eq.), (b) fossil depletion (kg oil eq.), (c) freshwater ecotoxicity (kg 1,4-DB eq.), (d) human toxicity, cancer (kg 1,4-DB eq.), and (e) marine.

in the studied category of photochemical ozone formation (17.06% and 21.76% for Scenarios A and B, respectively) that affects human health.[16,18,33,34]

The improved environmental impacts observed in Scenarios A and B are attributed to the advanced and integrated treatment methods for wastewater and solid wastes within the brewery. In Scenario A, wastewater undergoes an aeration process, which introduces oxygen to promote the breakdown of organic matter by aerobic microorganisms, significantly reducing organic pollutants.[4] The subsequent membrane filtration further purifies the water by removing residual contaminants, resulting in clean water suitable for discharge.[5,35] This dual treatment process minimizes the ecological footprint by ensuring that the discharged water meets high environmental standards, reducing marine and freshwater ecotoxicity.

Simultaneously, solid wastes in Scenario A are processed in an anaerobic digester, where anaerobic microorganisms decompose organic material in the absence of oxygen, producing biogas primarily composed of methane and carbon dioxide.[7,36] After enhancing the methane concentration by removing CO_2, the biogas is utilized in cogeneration units to produce both electricity and heat. This valorization of solid waste into renewable energy not only reduces greenhouse gas emissions but also lessens dependence on fossil fuels, leading to a significant decrease in fossil fuel consumption and associated emissions.

Scenario B employs a more elaborate wastewater treatment process, starting with screening to remove large solids, followed by treatment in a membrane bioreactor (MBR). The MBR combines biological degradation and membrane filtration, efficiently removing organic and inorganic pollutants.[37,38] The final UV treatment disinfects the water, ensuring that it is safe for reuse within the brewery or for discharge into aquatic ecosystems.[39,40] This comprehensive treatment process further enhances water quality and reduces environmental pollution.

For solid waste treatment in Scenario B, gasification is used. In this process, solid wastes, mainly spent grains, are converted into hydrogen gas through a high-temperature reaction in the presence of a controlled amount of oxygen. The resulting hydrogen can then be used to generate electricity and thermal energy, contributing to the brewery's energy needs.[26] The production of energy from waste materials reduces the reliance on conventional fossil fuels and lowers greenhouse gas emissions.

In both scenarios, the production of thermal energy and electricity from waste valorization is represented as thermal and electricity credits. These credits positively impact the environmental footprint by offsetting the need for fossil fuel-based energy generation, thereby reducing overall greenhouse gas emissions and other pollutants.[41] The integrated waste treatment and valorization processes demonstrate how breweries can achieve significant environmental benefits by adopting sustainable and circular economy practices.

The broader implications of these findings for the brewing industry and similar sectors are significant. By adopting these advanced waste treatments and valorization technologies, breweries can drastically reduce their environmental footprint, contribute to sustainability, and align with circular economy principles. This approach not only enhances environmental performance but also offers potential cost savings through energy production and waste reduction. These practices can serve as a model for other industries aiming to mitigate their environmental impact and promote sustainable production methods.

A direct comparison of base case scenarios and Scenarios A and B is shown in Fig. 7, and the overall reduction in environmental footprint is summarized in Table 4. Moreover, the endpoints of the ReCiPe methodology applied in the present work are depicted in Fig. 8 and Table 5.

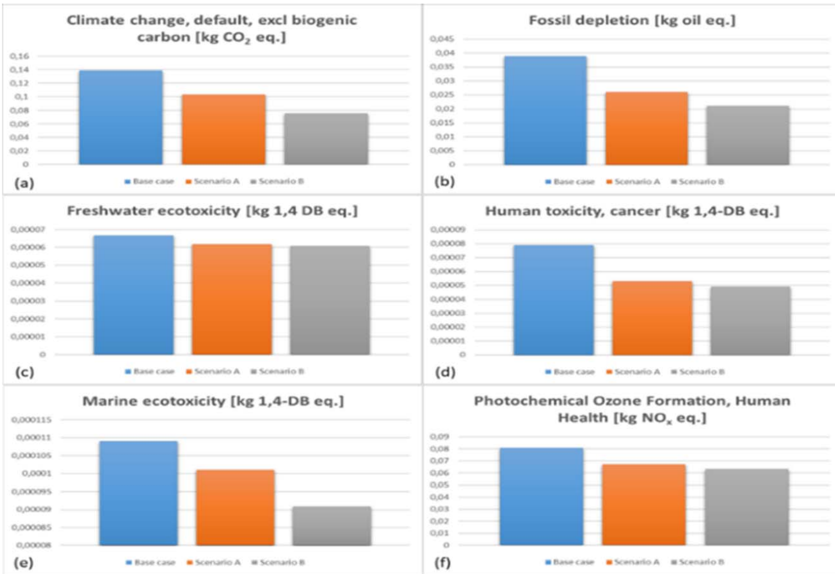

Fig. 7 Comparison of the environmental impact of the base case scenario and the two alternative scenarios on (a) climate change, default, excl biogenic carbon (kg CO_2 eq.), (b) fossil depletion (kg oil eq.), (c) freshwater ecotoxicity (kg 1,4-DB eq.), (d) human toxicity, cancer (kg 1,4-DB eq.), (e) marine ecotoxicity (kg 1,4-DB eq.), and (f) photochemical ozone formation, human health (kg NO_x eq.).

Table 4 Comparison of the environmental impact of the base case scenario and the two alternative scenarios on the studied categories

Impact category ($\times 10^{-3}$)	Base case scenario	Scenario A	Reduction in Scenario A (%)	Scenario B	Reduction in Scenario B (%)
Climate change, default, excl biogenic carbon [kg CO_2 eq.]	139.0	103.0	25.90%	75.5	45.68%
Fossil depletion [kg oil eq.]	38.9	26.0	33.16%	21.2	45.50%
Freshwater ecotoxicity [kg 1,4 DB eq.]	0.0666	0.0617	7.36%	0.0608	8.71%
Human toxicity, cancer [kg 1,4-DB eq.]	0.0791	0.0531	32.87%	0.0489	38.18%
Marine ecotoxicity [kg 1,4-DB eq.]	0.109	0.101	7.34%	0.0909	16.61%
Photochemical ozone formation, human health [kg NO_x eq.]	80.9	67.1	17.06%	63.3	21.76%

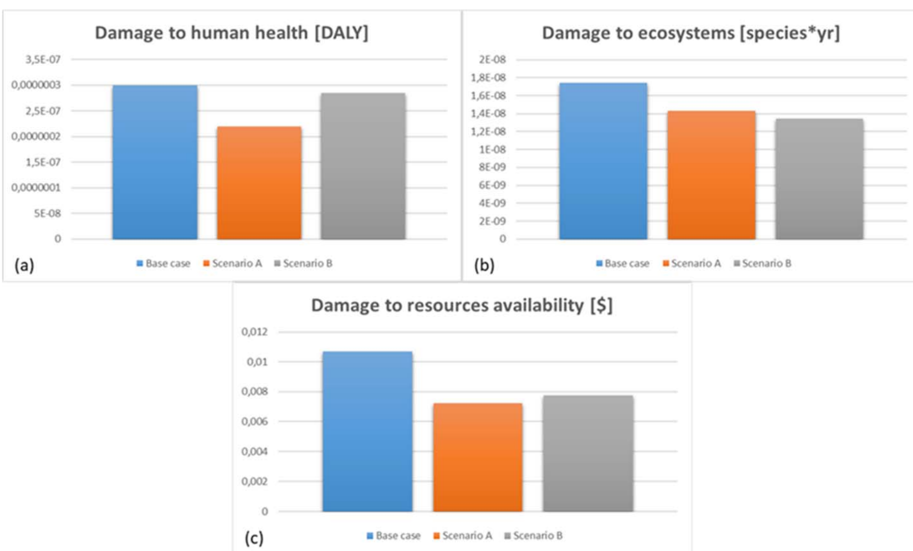

Fig. 8 Comparison of the ReCiPe endpoints of the base case scenario and the two alternative scenarios.

Table 5 ReCiPe endpoints of the base case scenario and the two alternative scenarios

Endpoint	Base case scenario	Scenario A	Reduction in Scenario A (%)	Scenario B	Reduction in Scenario B (%)
Damage to human health [DALY]	2.99×10^{-7}	2.20×10^{-7}	26.60%	2.84×10^{-7}	5.01%
Damage to ecosystems [species × years]	1.74×10^{-8}	1.43×10^{-8}	17.79%	1.34×10^{-8}	22.78%
Damage to resource availability [$]	1.07×10^{-2}	7.22×10^{-3}	32.61%	7.75×10^{-3}	27.68%

Table 6 Uncertainty analysis of anaerobic digestion (Scenario A) and gasification (Scenario B)

	Scenario A anaerobic digestion			Scenario B gasificatiom		
Impact category ($\times 10^{-3}$)	Low efficiency	Medium efficiency	High efficiency	Low efficiency	Medium efficiency	High efficiency
Climate change, default, excl biogenic carbon [kg CO_2 eq.]	+1.2%	103.0	−1.3%	+0.9%	75.5	−1.0%
Fossil depletion [kg oil eq.]	+2.1%	26.0	−2.1%	+1.8%	21.2	−1.8%
Freshwater ecotoxicity [kg 1,4 DB eq.]	—	0.0617	—	—	0.0608	—
Human toxicity, cancer [kg 1,4-DB eq.]	+0.2%	0.0531	−0.2%	+0.1%	0.0489	−0.1%
Marine ecotoxicity [kg 1,4-DB eq.]	—	0.101	—	—	0.0909	—
Photochemical ozone formation, human health [kg NO_x eq.]	+0.8%	67.1	−0.8%	+0.6%	63.3	−0.6%

According to the attained results, the adoption of innovative methods targeting wastewater purification, and repurposing of solid waste for energy production has notably enhanced the environmental impact of the brewing industry across all examined aspects in both Scenarios A and B. A direct comparison between the two studied alternative scenarios reveals that in the studied categories depicted in the present study, Scenario B exhibits a slighter enhanced environmental footprint compared to Scenario A. Moreover, the obtained endpoints from the ReCiPe methodology validate the significance of incorporating the studied wastewater treatment and solid waste valorization methods; as for the two studied scenarios, the damages to human health, ecosystems and resource availability are significantly lower compared to those of the base case scenario. In contrast to the studied categories, Scenario A exhibits lower values regarding the damage to human health and to resource availability compared to Scenario B. This can be attributed to the additional incorporation of other indicators (presented in the supplementary material) and to the larger electricity consumption in the treatment of wastewater and the valorization of solid wastes in Scenario B compared to Scenario A, respectively.

Uncertainty analysis

The results of the uncertainty analysis are presented in Table 6.

According to the results of the uncertainty analysis, it is evident that the environmental footprint of the two studied alternative scenarios does not change significantly as a function of the anaerobic digester's biogas production and gasification's hydrogen production capacity. However, in both cases the high efficiency of the studied methods resulted in a slightly improved environmental performance, and the low efficiency, in a slight increase in the environmental footprint in certain categories, such as greenhouse gas emissions.

Future perspectives and recommendations

The adoption of the studied waste treatment technologies in the beer production industry comes with a set of specific recommendations, potential barriers, and strategies to overcome these challenges. The necessity for overcoming any difficulties is also highlighted by the fact that spent grains and other by-products from the brewing industry, such as brewer's yeast and hop residues, are increasingly recognized for their potential in enhancing the food chain due to their rich nutritional content. Spent grains, the most abundant by-product, are particularly high in proteins, dietary fibers, essential amino acids, and antioxidants. These can be processed into protein-rich supplements and fiber-enriched flours, which can be incorporated into bread, snacks, and other baked goods to improve their nutritional profiles. Additionally, brewer's yeast, a by-product rich in vitamins, proteins, and minerals, can be used as a nutritional supplement or flavor enhancer in various food products. Hop residues, which contain potent antioxidants like polyphenols and flavonoids, can be utilized to create functional food ingredients that offer health benefits such as reducing oxidative stress and inflammation. By integrating these by-products into the food chain, the brewing industry can significantly reduce waste, contribute to more sustainable food production systems, and provide innovative, health-promoting ingredients for consumers.[2,4,7]

First, comprehensive feasibility studies are crucial. These studies should include technical, economic, and environmental assessments to ensure that the proposed waste treatment methods are suitable and beneficial for specific breweries. However, the initial cost and time investment for these studies can be significant barriers. To mitigate this, breweries can seek funding from government grants or industry partnerships and collaborate with academic institutions to reduce costs.[42]

Implementing pilot projects or demonstration plants is another vital recommendation. These projects showcase the effectiveness of the new technologies in real-world settings. The initial financial investment and potential operational disruptions during this phase pose challenges. To address these, subsidies and financial incentives from government bodies or environmental agencies can be utilized, and pilot projects can be planned in phases to minimize disruptions.[42,43]

Training and capacity building are essential for the successful adoption of new technologies. Extensive training programs should be provided to brewery staff and management on the operation and maintenance of new waste treatment systems. Resistance to change and lack of technical expertise among existing staff are potential barriers. Developing partnerships with technology providers for training sessions and offering incentives for staff participation can help overcome these challenges.

Financial incentives and support are crucial for encouraging breweries to invest in new technologies. Tax breaks, low-interest loans, and grants can support initial investments. Lack of awareness or access to these financial support mechanisms can be a barrier. Engaging with local and national governments to create awareness and streamline the application process for financial incentives is a practical strategy to overcome this barrier.[42,43]

Regulatory support and a conducive policy framework are necessary to promote the adoption of sustainable waste treatment technologies. However, slow policy changes and regulatory approvals can hinder progress. Participating in industry associations to collectively advocate for regulatory changes and engaging in continuous dialogue with policymakers can facilitate faster policy support.[44]

Conducting detailed cost-benefit analyses can highlight the long-term economic benefits and environmental savings of adopting new technologies. A common barrier is the short-term cost focus among stakeholders. Presenting case studies and data from pilot projects to demonstrate long-term savings and environmental benefits can help shift this focus.[44]

Increasing public awareness and community engagement about the environmental benefits of the new waste treatment technologies is also important. Limited public knowledge about industrial waste management practices can be a barrier. Launching public awareness campaigns and involving local communities in pilot projects can demonstrate the benefits firsthand and garner public support.[42,45]

Fostering collaborations and partnerships between breweries, technology providers, research institutions, and environmental organizations can facilitate technology transfer and shared learning. Competitive concerns and lack of trust between different stakeholders can be barriers. Establishing formal agreements and creating neutral platforms for knowledge sharing and collaboration can help overcome these challenges.

Despite these recommendations, several potential barriers to implementation exist. High initial costs are a significant barrier, but securing funding through government grants, subsidies, and financial incentives, as well as exploring financing options like green bonds or public-private partnerships, can address this issue.[44]

Technical challenges and a lack of expertise can also hinder implementation. Investing in comprehensive training programs and collaborating with technology providers for ongoing support can mitigate these challenges.[46]

Regulatory and policy hurdles can delay the adoption of new technologies. Advocacy for policy changes through industry associations and maintaining active engagement with regulatory bodies can expedite approval processes.

Operational disruptions during the implementation of new systems are another barrier. Planning and executing the implementation in phases and utilizing off-peak production periods for major changes can minimize these disruptions.[46]

Lastly, cultural resistance to change among staff and management can impede progress. Fostering a culture of sustainability within the organization, highlighting long-term benefits, and involving employees in the decision-making process can help gain their buy-in and overcome resistance.

By addressing these barriers with targeted strategies, breweries can effectively adopt and benefit from advanced waste treatment technologies, leading to improved environmental performance and operational efficiencies.

Application in the wine industry

The approach of employing advanced waste treatment and valorization methods, as demonstrated in the brewing industry, can similarly be applied to the wine industry to enhance its environmental sustainability. The wine industry also faces challenges related to high energy consumption, substantial water usage, and significant waste generation. By adopting anaerobic digestion coupled with cogeneration units, the industry can convert organic waste into biogas, which can then be used to generate heat and electricity, thereby reducing reliance on fossil fuels and decreasing greenhouse gas emissions. Additionally, incorporating aeration and membrane filtration treatments can help recycle water within the winery, ensuring efficient water use and minimizing the impact on local water resources.[38,47,48]

Furthermore, the wine industry can benefit from the use of gasification, screening, membrane bioreactors, and UV treatment techniques to manage waste more effectively. Gasification of solid wastes such as grape marc and vine prunings can produce hydrogen-rich syngas, providing a renewable energy source and reducing waste disposal issues. The implementation of membrane bioreactors and UV treatments can improve the quality of wastewater discharged from wineries, making it safe for aquatic ecosystems and potentially suitable for reuse in vineyard irrigation. By integrating these waste treatment and valorization processes, the wine industry can achieve significant reductions in greenhouse gas emissions and overall environmental impact, fostering a more sustainable and environmentally friendly production cycle.[49,50]

The application of advanced waste treatment and valorization methods in the wine industry can bridge several critical gaps in environmental sustainability. One significant gap is the high energy consumption associated with traditional waste management practices. By adopting anaerobic digestion and cogeneration units, wineries can convert organic waste into biogas, subsequently generating renewable heat and electricity, thereby reducing their reliance on fossil fuels and lowering greenhouse gas emissions. Another gap is the substantial water usage in wine production. Implementing aeration and membrane filtration treatments enables water recycling within wineries, minimizing freshwater withdrawals and reducing the environmental impact on local water resources. Additionally, the challenge of managing solid wastes such as grape marc and vine prunings can be effectively addressed through gasification, which converts these wastes into hydrogen-rich syngas, providing a renewable energy source and mitigating waste disposal issues. Furthermore, the use of membrane bioreactors and UV treatments enhances wastewater quality, making it suitable for safe discharge or reuse in vineyard irrigation, thus promoting a circular economy and significantly reducing the overall environmental footprint of the wine industry.[45]

Conclusions

Two distinct scenarios of wastewater and solid waste treatment within the brewing industry were studied to gauge their environmental impact using LCA analysis and were compared to a conventional scenario of solid waste and wastewater handling. The conventional scenario involved transporting wastewater to a municipal treatment facility, while non-hazardous solid waste was disposed of in landfills. In contrast, the alternative scenarios applied wastewater purification and solid waste valorization, aiming at energy production, methods within the industry's boundaries. Generally, employing suitable waste treatment technologies significantly lessened the environmental impact of the case study. Among the examined wastewater and solid waste treatment technologies in the alternative scenarios, anaerobic digestion and gasification stood out due to the energy and heat generated *via* cogeneration, thus showcasing superior environmental performance. Moreover, the water obtained in the alternative scenarios meets high environmental standards, making it suitable for reuse within the industry to mitigate environmental impact or for various purposes such as agriculture or safe discharge into aquatic environments. The findings of this research suggest that the proposed technologies could advance the sustainable production of beer and alcoholic beverages within the industrial sector. Generally, Scenario A exhibited slightly lower values regarding the damage to human health and resource availability, while Scenario B depicted a lower value of damage to ecosystems and to the studied categories, such as greenhouse gas emissions and marine and freshwater ecotoxicity. Additionally, this methodology can be broadly applied to analyze the environmental impacts of various food production systems and pinpoint areas needing substantial improvement. In conclusion, the study emphasizes the importance for industries to prioritize environmentally friendly methods over conventional ones, integrating efficient approaches for wastewater treatment and waste utilization to bolster sustainability and embrace the principles of a circular economy. This necessitates a focus on exploring innovative methods and documenting their environmental and energy benefits through life cycle assessment studies. Finally, despite the promising findings, the study's limitations include its confinement to a single case in the brewing industry, which may limit generalizability, and reliance on specific assumptions about waste treatment efficiencies. Future research should broaden the analysis to include diverse breweries and geographical locations, investigate emerging technologies, and consider the social and economic dimensions to ensure comprehensive insights and facilitate broader adoption.

Data availability

The data supporting the findings of this study are available within the article. Additional datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflicts of interest

There are no conflicts to declare.

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