Magnetite-Enhanced Anaerobic Digestion for Brewery Wastewater: Advancing Biogas Recovery and Circular Treatment Strategies

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***Abstract*—Anaerobic digestion (AD) has long been recognized as a sustainable approach for brewery wastewater treatment, enabling simultaneous pollutant reduction and renewable energy recovery in the form of biogas. However, conventional AD systems often suffer from instability, long start-up periods, and reduced efficiency under high-strength organic loads. Recent studies highlight the role of magnetite nanoparticles** (Fe_3O_4) in enhancing AD performance by improving direct **interspecies electron transfer, buffering pH, reducing volatile fatty acid accumulation, and stabilizing microbial communities. Reported improvements include methane yield increase of 15–40%, chemical oxygen demand removal efficiencies exceeding 80%, and shortened hydraulic retention times. Their magnetic nature further allows separation and reuse, aligning with circular economy principles. This review systematically examines published studies between 2016 and 2025, focusing on brewery wastewater characterization, the mechanisms through which magnetite enhances AD, comparative reactor performance, and operating factors affecting treatment efficiency. Research gaps are identified in scaling up to industrial conditions, nanoparticle recovery, and long-term environmental safety. Overall, magnetite-assisted AD offers a promising pathway toward eco-friendly, cost-effective, and energy-positive brewery wastewater management.**

***Keywords*— Anaerobic Digestion, Biogas Production, Brewery Wastewater, Magnetite Nanoparticles, Methane Yield.**

I. INTRODUCTION

The global brewing industry is experiencing rapid growth, driven by rising consumer demand, urbanization, and economic development. However, this expansion has increased environmental pressures, particularly in the discharge of high-strength brewery wastewater in municipal waterworks. Brewery effluents contain elevated levels of chemical oxygen demand (COD), biological oxygen demand (BOD), turbidity, colour, and nutrients such as nitrogen and phosphorus, making them one of the most polluting forms of industrial waste [1].

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If discharged untreated, these effluents pose a serious threat to aquatic ecosystems and human health, violating environmental regulations and sustainability targets. As a result, there is a growing need for breweries to adopt cost-effective, environmentally friendly wastewater treatment technologies that align with global sustainability goals. Anaerobic digestion (AD) has proven to be a reliable and widely adopted method for treating brewery wastewater. It offers the dual benefit of reducing organic pollutants while generating biogas, a renewable form of energy that can be harnessed for heating, electricity, or fuel [2]. The AD process aligns with the principles of green engineering and circular economy, allowing breweries to reduce waste, lower carbon emissions, and recover valuable resources. However, AD systems can suffer from inefficiencies such as long startup periods, low degradation rates under high organic loading rates, pH fluctuations, and accumulation of volatile fatty acids that inhibit microbial activity [3]. These limitations have prompted researchers to explore enhancements using advanced technologies.

Among these innovations, the application of magnetite (Fe_3O_4) nanoparticles has gained growing attention for their ability to improve the AD performance significantly [4],[5]. Magnetite nanoparticles are iron-based materials with a high surface area (typically 50–150 m²/g), magnetic properties, and excellent electrical conductivity [6]. When introduced into AD systems, they facilitate direct interspecies electron transfer (DIET) between microbial communities, particularly between syntrophic bacteria and methanogens, which accelerates the breakdown of complex organic compounds and enhances methane production [7]. Additionally, they help buffer pH, reduce the accumulation of volatile fatty acids, and promote microbial stability, making them ideal additives for treating variable industrial effluents, particularly brewery wastewater streams [8]. In brewery wastewater systems, where high organic loads and fluctuating feed compositions are common, magnetite nanoparticles have shown the potential to improve process stability, increase methane yield, and reduce hydraulic retention times [9]. Moreover, their magnetic nature allows for easier separation and potential reuse, contributing to sustainable material management [10]. Despite the growing number of studies investigating these effects in laboratory-scale experiments, research findings remain fragmented and inconsistent across reactor configurations, nanoparticle dosages, microbial inoculum sources, and operational conditions. Without a consolidated and critical evaluation of these studies, it is difficult to extract transferable insights or make informed decisions for scaling up and implementing magnetite-assisted systems in real-world brewery operations.

As such, the current review addresses that gap by synthesizing published research from 2016 to 2025 on the application of magnetite nanoparticles in brewery wastewater treatment via anaerobic digestion. Its objectives are to study the composition of brewery wastewater, assess the role of magnetite nanoparticles in enhancing biogas production, compare operational and design parameters across studies, evaluate the technical performance of different AD systems, and identify challenges, research gaps, and future opportunities for industrial-scale implementation.

The review aims to support researchers, engineers, and decision-makers in developing scalable, eco-efficient systems that enhance energy recovery, reduce pollution, and transition brewery operations toward sustainable, climate-resilient practices.

II. Methodology

Using the Scopus and Web of Science (WoS) databases, research trends on articles published on the use of magnetite nanoparticles for brewery wastewater treatment and related processes were assessed. Keywords, i.e., “magnetite nanoparticles” OR “Fe_3O_4” AND “brewery wastewater” OR “industrial effluent” OR “biogas production” OR “anaerobic digestion” OR “treatment efficiency” OR “methane yield” were used for the search, restricted to English-language peer-reviewed research articles published between 2016 and 2025. The WoS search showed a growing number of publications in this field, as illustrated in “Fig.1”, while the

Scopus results are shown in Figure 2.

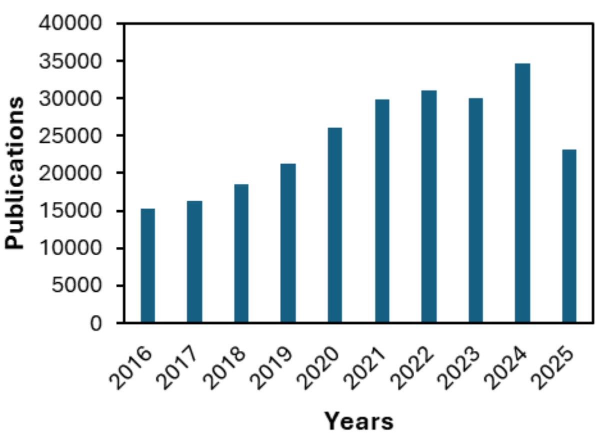

Fig. 1. Web of Science publications for eco-friendly brewery wastewater

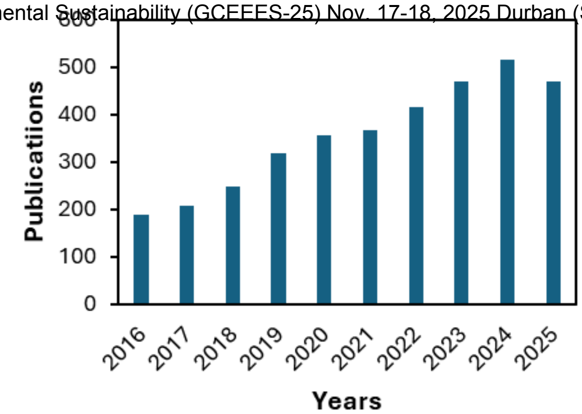

Fig. 2. SCOPUS publication for eco-friendly brewery wastewater

It can be observed from both figures that there has been a steady increase in publications after 2018, with a more pronounced rise from 2021 to 2025. This upward trend indicates that the integration of magnetite nanoparticles in anaerobic digestion and wastewater treatment is attracting increasing attention, likely due to its potential to enhance treatment efficiency and methane yield while aligning with eco-friendly and sustainable engineering goals. However, the combined search results show that studies specifically focusing on brewery wastewater remain limited compared to the broader research on magnetite nanoparticles in wastewater treatment. Much of the existing work targets general industrial effluent or municipal wastewater, with fewer investigations exploring brewery wastewater's unique high-strength organic load and variable composition. Furthermore, studies that combine nanoparticle-assisted anaerobic digestion with quantitative assessment of treatment efficiency, methane yield, and COD/turbidity reduction are scarce.

The findings of the present study explicitly indicate a clear research gap in the targeted application of magnetite nanoparticles for optimizing biogas production from brewery wastewater, especially when considering industrial scalability, process economics, and environmental impact. Therefore, there is an opportunity for in-depth experimental studies and techno-environmental evaluations that can bridge this gap and contribute to the advancement of eco-friendly brewery wastewater management strategies.

III. Discussion

A. *Characterization of Brewery Wastewater Composition*

Table 1 presents a compilation of physicochemical parameters of brewery wastewater reported in different studies, together with corresponding anaerobic digestion treatment efficiencies. These parameters, including pH, COD, Total Suspended Solids**,** Volatile Suspended Solids**,** Total Solids**,** nitrogen, and phosphorus concentrations, provide insight into the complex composition of brewery effluent. Understanding these values is essential, as they directly influence anaerobic digestion performance, methane yield, and environmental impact if discharged untreated.

TABLE I: COMPILATION OF REPORTED BREWERY WASTEWATER PARAMETERS FROM VARIOUS STUDIES AND CORRESPONDING ANAEROBIC DIGESTER TREATMENT EFFICIENCIES.

Parameter	Reference		
	[2]	[3]	[4]
pH	4.6-7.3	3.3-6.3	6.3-6.9
Temp. (ºC)	24-30.5	25-35	-
COD (mg/L)	1096-8926	8240≥ 20000	910-1900
TSS (mg/L)	530-3728	2020-5940	140-320
VSS (mg/L)	804 –1278	-	90 –180
TS (mg/L)	0.48–13.05	5100 –8750	1300–2000
NH_4-N (mg/L)	0.48–13.05	-	2.2 – 7.0
TN (mg/L)	0 –5.36	0.0196–0.0336	17-36
TP (mg/L)	-	16-123	8.4-17
COD removal (%)	79	57	80

It can be observed from Table 1 that brewery wastewater is characterised by a wide range of physicochemical parameters, reflecting its high-strength organic load and variable composition. For instance, COD values reported are as high as 20,000 mg/L, which is significantly higher than those of typical municipal wastewater. Such elevated COD levels arise from the presence of residual sugars, alcohol, yeast cells, and other organic compounds generated during brewing and fermentation. If discharged untreated into water receiving bodies, high-COD effluent can deplete dissolved oxygen in receiving water bodies, leading to eutrophication and the death of aquatic organisms such as fish. The pH of brewery astewater varies broadly (3.0–12.0), depending on the stage of production and cleaning processes. Acidic pH conditions typically result from fermentation and cleaning with acidic detergents, while alkaline values are often linked to caustic cleaning-in-place (CIP) chemicals. Extreme pH conditions negatively affect microbial stability in anaerobic digesters, making pH regulation critical for efficient wastewater treatment. Temperature ranges (18–40 °C) generally reflect seasonal variations and brewery operations. Since microbial activity in AD is highly temperature-dependent, such variations can directly influence the rate of biogas production and process stability. High levels of Total Suspended Solids (TSS) and Volatile Suspended Solids (VSS) (up to ~6000 mg/L) are linked to the presence of spent grains, yeast, and other particulate residues from brewing. Excessive solids can cause sludge accumulation, reduce digester efficiency, and increase sludge management costs. Nutrients such as ammonium nitrogen (NH_4^+-N), total nitrogen (TN), and total phosphorus (TP) are also reported. Nitrogen originates mainly from yeast and protein residues, while phosphorus is introduced via raw materials and cleaning chemicals. Although these nutrients are essential for microbial growth, their excessive discharge contributes to eutrophication of receiving water bodies. Finally, the reported COD removal efficiencies (up to 80%) indicate that anaerobic digestion can successfully reduce pollutant loads. However, the efficiency strongly depends on maintaining optimal operating conditions. Without treatment, brewery wastewater with such characteristics poses a high risk of environmental degradation but simultaneously offers excellent potential for renewable energy recovery through methane production.

B. Mechanisms Governing Anaerobic Digestion and the Role of Magnetite Nanoparticles

The AD process is a multi-stage biochemical process in which complex organic matter is converted into biogas, primarily methane (CH_4) and carbon dioxide (CO_2), under oxygen-free conditions. This process is driven by a consortium of microorganisms, each responsible for specific metabolic stages that occur sequentially yet interdependently. The efficiency of an AD process depends on operational conditions such as pH, temperature, organic loading rate (OLR), and hydraulic retention time (HRT), as well as on the enhancement strategies applied to accelerate microbial activity. The introduction of magnetite nanoparticles (Fe_3O_4) has emerged as an innovative approach to intensify AD performance by improving microbial electron transfer, stabilizing the process, and enhancing methane yield [6]. The following subsections discuss each stage, hydrolysis, acidogenesis, acetogenesis, and methanogenesis in detail, along with the role of magnetite nanoparticles in intensifying their performance.

1) Hydrolysis

In hydrolysis, complex organic macromolecules such as proteins, carbohydrates, and lipids are enzymatically broken down into soluble monomers (amino acids, sugars, and fatty acids) by hydrolytic bacteria. This step is often rate-limiting for substrates with high particulate organic matter [7]. Equation (1) presents the general reaction for carbohydrate hydrolysis [6].

$$(C_6H_{12}O_5)_n + nH_2O \rightarrow nC_6H_{12}O_6 \tag{1}$$

Magnetite nanoparticles can improve hydrolysis by promoting the adsorption of enzymes on their surface and facilitating better contact between microorganisms and substrates, thereby increasing hydrolytic efficiency [8].

2) Acidogenesis

During acidogenesis, the monomers produced in hydrolysis are converted by fermentative bacteria into short-chain volatile fatty acids (VFAs), alcohols, hydrogen (H_2), and CO_2. Forexample, glucose fermentation can be represented as:

$$C_6H_{12}O_6 \rightarrow 2CH_3CH_2OH + 2CO_2 \tag{2}$$

Or

$$C_6H_{12}O_6 + 2H_2O \rightarrow 2CH_3COOH + 2CO_2 + 4H_2 \quad (3)$$

Magnetite nanoparticles facilitate DIET between acidogens and methanogens, reducing the need for hydrogen-mediated electron transfer and leading to more stable acidogenesis[9]

3) Acetogenesis

In acetogenesis, VFAs and alcohols are oxidized to acetic acid, H_2, and CO_2 by acetogenic bacteria, which serve as precursors for methanogenesis[10]. For instance, propionate oxidation proceeds as follows:

$$CH_3CH_2COO^- + 3H_2O \rightarrow CH_3COO^- + H^+ + HCO_3^- + 3H_2 \quad (4)$$

This stage is thermodynamically unfavourable under high hydrogen partial pressure; however, magnetite nanoparticles act as conductive materials, accelerating electron transfer and maintaining low hydrogen concentrations to favour acetogenesis [11].

4) Methanogenesis

Methanogenesis is the final stage, carried out by methanogenic archaea, in which methane is produced via two main pathways: acetoclastic methanogenesis and hydrogenotrophic methanogenesis[10]. The reactions are:

Acetoclastic methanogenesis:

$$CH_3COOH \rightarrow CH_4 + CO_2 \quad (5)$$

Hydrogenotrophic methanogenesis:

$$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O \quad (6)$$

The incorporation of magnetite (Fe_3O_4) nanoparticles into anaerobic digestion (AD) systems has been demonstrated to significantly enhance biogas yield, process stability, and organic matter degradation efficiency. Magnetite serves as an effective conductive material, facilitating DIET between syntrophic bacteria and methanogenic archaea, thereby bypassing the conventional hydrogen-mediated electron transfer pathway [12]. This mechanism accelerates the rate-limiting methanogenesis stage, particularly the acetoclastic and hydrogenotrophic pathways, as described in (5) and (6). In the presence of magnetite nanoparticles, electron transfer from fermentative bacteria to methanogens is enhanced due to the nanoparticles' high conductivity and surface reactivity. This reduces the accumulation of VFAs and hydrogen, stabilizing pH and maintaining optimal redox potential for methanogenic activity [13]. Furthermore, Fe^{2+} and Fe^{3+} ions released from magnetite dissolution participate in Fenton-like reactions, can degrade refractory organics, and improve overall biodegradability [14]. Magnetite nanoparticles also act as a micronutrient source for methanogens, particularly for the synthesis of cytochromes and iron–sulfur clusters that are essential components of electron transport proteins in methanogenesis [15] In addition, magnetite can adsorb inhibitory compounds such as ammonia and sulfide, thus reducing their toxicity in AD systems [16]. Studies have reported methane yield improvements ranging from 15% to over 40% when magnetite is applied at optimal dosages (typically 20–200 mg/L, depending on substrate characteristics and digester configuration)[17],[18].

Additionally, magnetite surfaces can adsorb inhibitory compounds such as ammonia and sulfide, reducing toxicity and promoting stable microbial growth [19]. Their high surface area further improves enzyme–substrate interactions, enhancing hydrolysis efficiency. Studies consistently report methane yield increases of 15–40% when magnetite is applied at optimized dosages (typically 20–200 mg/L), with added benefits of shorter hydraulic retention times and improved resistance to process shocks [20].

Overall, the synergistic effects of improved electron transfer, micronutrient supplementation, inhibitory compound adsorption, and enhanced enzymatic activity position magnetite nanoparticles as a promising additive for optimizing the anaerobic digestion of brewery wastewater and other high-strength organic waste streams. Magnetite nanoparticles improve both stability and productivity of AD systems treating high-strength wastewaters.

C. Role of Magnetite Nanoparticles in Anaerobic Digestion

Table II summarises selected studies on anaerobic digestion for wastewater treatment and biogas production, comparing different substrates, reactor configurations, and additives, including magnetite nanoparticles. The table highlights how conventional AD systems have performed with brewery wastewater and how enhancements such as conductive additives improve methane yields, COD removal, and process stability. This comparison allows for a clearer evaluation of the role of magnetite nanoparticles within the broader context of wastewater treatment technologies.

Table II provides a comparative summary of studies on anaerobic digestion (AD) of brewery wastewater without the application of nanoparticles. Most studies employed full-scale Upflow Anaerobic Sludge Blanket (UASB) reactors. Fang et al. [13] reported stable long-term methanogenesis with COD removal efficiencies of up to 80% when anaerobic sludge was seeded and alkalinity was maintained with sodium bicarbonate. Yang et al. [12] observed COD removal efficiencies between 57–79% and methane yields of approximately 0.25–0.30 m^3 CH_4/kg COD removed under tropical conditions when activated sludge was used as inoculum. These results demonstrate that brewery wastewater can be effectively treated in UASB systems, although performance depends on inoculum quality and buffering capacity.

Granular sludge-based UASB reactors [27] achieved COD removals of ~80% with methane contents of 65–70%, indicating the importance of biomass structure and trace metals in sustaining methanogenic activity. Menon and Kalyanraman [29] employed a UASB reactor with CO_2 absorption for pH regulation, achieving COD removal of ~80% and stable methane production despite alkaline influent variability.

TABLE II: Compilation of Studies on Anaerobic Digestion for Wastewater Treatment without Nanoparticle Additives

Study	Substrate	Reactor Type	Additive / Chemical Used	Key Findings
[13]	Brewery wastewater	Full-scale UASB	Seeded with anaerobic sludge; alkalinity maintained with $NaHCO_3$	COD removal up to 80%; stable long-term methanogenesis.
[12]	Brewery wastewater (tropical climate)	Full-scale UASB	Inoculated with activated sludge; natural buffering capacity used	COD removal 57–79%; methane yield ~0.25–0.30 m³ CH_4/kg COD removed.
[1]	Brewery wastewater	UASB granules	Granular methanogenic biomass with trace metals naturally present	COD removal ~80%; methane content ~65–70% of biogas.
[28]	Brewery wastewater	Full-scale UASB	Native brewery sludge with background nutrients (N, P, Fe)	COD removal ~80%; methane yield ~0.28 m³ CH_4/kg COD.
[29]	Brewery wastewater	UASB with absorber	Carbon dioxide (CO_2) injection for pH control	COD removal ~80%; stable methane production despite alkaline influent.

TABLE II: Compilation of Studies on Anaerobic Digestion for Wastewater Treatment with Nanoparticle/Conductive Additives.

Study	Substrate	Reactor Type	Additive / Chemical Used	Key Findings
[23]	Synthetic wastewater (acetate, propionate, glucose)	Batch AD	Magnetite nanoparticles (Fe_3O_4)	Methane yield ↑ 20–30%; VFA accumulation reduced ~25%.
[10]	Food waste	Solid-State AD	Magnetite nanoparticles (Fe_3O_4)	Methane yield ↑ 18–25%; HRT reduced by ~20%.
[30]	Various substrates	Review	Conductive materials: iron nanoparticles, biochar, granular sludge	Reported methane yield ↑ 15–40% with magnetite compared to controls.
[1]	Sugar refinery wastewater	Batch AD	$AlFe_2O_4$ and $MgFe_2O_4$ nanoparticles	Methane yield ↑ 25–40%; COD removal ↑ ~15% vs. control.
[31]	Mixed wastewater	Anaerobic membrane bioreactor (AnMBR)	Fe_2O_3–biochar composites	Methane yield ↑ ~22%; COD removal 85–90%; biofouling reduced ~30%.

Similarly, Carter et al. [28], using native brewery sludge and background nutrients, achieved COD removals of ~80% with methane yields of ~0.28 m³ CH_4/kg COD. Collectively, these studies confirm that UASB reactors are robust technologies for brewery wastewater treatment, though their performance is influenced by sludge quality, buffering strategies, and influent composition.

Table II presents studies on nanoparticle-assisted AD systems. Aworanti et al. [23] reported methane yield increases of 20–30% and reductions in volatile fatty acid accumulation of approximately 25% when magnetite (Fe_3O_4) nanoparticles were applied in batch AD of synthetic wastewater. Ni et al. [10] achieved methane yield improvements of 18–25% and reductions in hydraulic retention time during solid-state AD of food waste with magnetite supplementation. These enhancements are attributed to the ability of magnetite to facilitate DIET, stabilize pH, and mitigate the effects of inhibitory compounds.

Other studies have explored alternative conductive materials. Enitan et al. [1] reported that $AlFe_2O_4$ and $MgFe_2O_4$ nanoparticles increased methane yields by 25–40% and improved COD removal by ~15% compared to control systems. Chatterjee and Mazumder [31] found that Fe_2O_3–biochar composites applied in anaerobic membrane bioreactors enhanced methane yields by ~22%, achieved COD removals of 85–90%, and reduced biofouling by ~30%. Review findings [30] consistently reported methane yield improvements of 15–40% across studies employing magnetite and other conductive materials.

The distinction between the two tables is clear: full-scale UASB systems treating brewery wastewater achieve high COD removals but moderate methane yields, whereas nanoparticle-assisted systems, typically at laboratory scale, consistently report enhanced methane yields and shorter retention times. While these findings highlight the potential of conductive additives, the scalability and long-term stability of nanoparticle-assisted AD systems require further investigation.

D. Key Operating Parameters Influencing Anaerobic Digestion Performance

AD performance is strongly influenced by environmental and operational parameters. Temperature is one of the most critical, as microbial consortia function optimally in mesophilic (35–37 °C) or thermophilic (50–55 °C) ranges; deviations can reduce metabolic activity and methane yield [21]. pH should remain near neutrality (6.8–7.2) to balance acidogenic and methanogenic activity, with alkalinity serving as an important buffer [22]. The organic loading rate (OLR) must be carefully controlled, as excessive organic input can lead to VFA accumulation and process inhibition [23]. Similarly, hydraulic retention time (HRT) determines the extent of substrate degradation, while low values risk biomass washout.

Other key factors include mixing intensity, which ensures substrate–microbe contact and prevents stratification; inhibitors, such as ammonia, sulfide, or heavy metals, which can suppress microbial activity [24], and the availability of trace nutrients such as Fe, Ni, Co, and Se, which are vital for enzymatic activity in methanogens [25]. The incorporation of conductive additives like magnetite nanoparticles can help mitigate many of these limitations by stabilizing pH, adsorbing inhibitors, and enhancing electron transfer.

E. Future Directions in Anaerobic Digestion for Wastewater Management

The integration of magnetite nanoparticles in AD presents significant opportunities, but several research gaps remain. Most current studies are laboratory-scale, highlighting the need for pilot- and full-scale demonstrations under real brewery conditions to assess long-term stability and reproducibility [6]. Environmental fate and recovery of magnetite nanoparticles require careful evaluation to ensure safe large-scale use, including strategies for magnetic separation and reuse[26].

Future research should also explore the use of hybrid additives, such as magnetite–biochar composites, which combine conductive and adsorptive properties [27]. Integration of nanoparticle-assisted AD into brewery operations can support circular economy models by enabling on-site energy recovery, reducing waste treatment costs, and contributing to carbon neutrality. Moreover, the adoption of digital monitoring and process control systems could optimize Organic Loading Rate, pH, and redox potential in real time, enhancing system resilience. With continued innovation, magnetite-assisted AD has the potential to become a mainstream industrial wastewater treatment technology.

IV. Conclusion

This review demonstrates that the AD process remains one of the most effective and sustainable methods for treating brewery wastewater while simultaneously producing renewable biogas. Conventional AD systems have been shown to achieve high COD removal and stable methane yields, yet they often face operational challenges such as pH fluctuations, volatile fatty acid accumulation, and extended retention times. The integration of magnetite (Fe_3O_4) nanoparticles has emerged as a promising solution to overcome these limitations.

Across various studies, magnetite nanoparticles enhanced biogas yield by 15–40%, stabilized microbial activity, improved hydrolysis and acetogenesis, and reduced process inhibition by adsorbing toxic compounds.

Their conductive properties facilitate direct interspecies electron transfer (DIET), accelerating methanogenesis and supporting greater process stability under high-strength and variable effluent conditions typical of brewery wastewater. Additionally, their potential for recovery and reuse aligns with circular economy and green engineering principles. However, while laboratory-scale evidence strongly supports the use of magnetite nanoparticles, full-scale industrial applications remain limited. Key research gaps include optimizing nanoparticle dosage for different wastewater compositions, evaluating long-term stability under real brewery conditions, and assessing the environmental fate of nanoparticles after repeated use. Addressing these gaps is essential to ensure both technical feasibility and environmental safety at larger scales.

Overall, magnetite-assisted anaerobic digestion represents a viable pathway toward eco-friendly brewery wastewater management. By coupling wastewater treatment with renewable energy recovery, this approach directly supports global sustainability targets, particularly the UN Sustainable Development Goals related to clean water, clean energy, responsible production, and climate action. With continued innovation, scaling, and integration into brewery operations, magnetite-enhanced AD could play a vital role in transforming brewery effluent from a pollution burden into a valuable resource for sustainable energy and circular economy practices.

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