

Sustainable Biohydrogen Production from Animal Manure: Review into Processes Optimization, Pretreatment Strategies, and Feedstocks Evaluation

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ABSTRACT

Transforming animal manure from an environmental liability into a renewable biohydrogen resource represents a promising strategy for simultaneously addressing waste management and clean energy production. A narrative comparative review was conducted based on the critical synthesis of 130 peer-reviewed publications. Comparative evaluation highlighted integrating Dark Fermentation (DF) and Photo Fermentation (PF) effectively exploits their complementary metabolic pathways, resulting in more efficient substrate utilization and enhanced biohydrogen recovery than either process alone. The review further demonstrated that combining pretreatment, operational optimization, and co-digestion consistently improved substrate accessibility, microbial activity, and overall fermentation performance. This combined approach enhances substrate conversion, supports microbial activity, and improves overall fermentation performance. Across diverse feedstocks including cow, pig, chicken, buffalo, and horse manure, reported biohydrogen yields ranged from 15.5–275.6 mL H₂/g-VS, while production rates reached up to 1383 mL H₂/L/day. The observed variability reflected differences in feedstock characteristics, pretreatment strategies, fermentation pathways, and operating conditions. Despite substantial technological advances, bridging the gap between laboratory findings and industrial implementation remains the principal challenge. Future research should therefore prioritize pilot-scale validation, integrated reactor engineering, techno-economic analysis, and life cycle assessment to accelerate commercial deployment.

Keywords: animal manure, biohydrogen production, co-digestion, sustainable bioenergy.

1. INTRODUCTION

These days clean energy is high in demand, so scientists are looking closely at biohydrogen, a fuel made from living things. It's a strong contender because it packs more power than many renewables, doesn't release carbon (C) when used, moreover can turn trash into usable energy, tackling waste issues simultaneously. Livestock creates lots of manure, which is interesting because it breaks down easily and holds plenty of nutrients. These qualities help microbes make hydrogen gas (H₂). So, using animal

manure both cleans up waste while also creating renewable energy a good fitting into plans for a more sustainable future [1–3]. Getting useful H₂ from animal waste isn't straightforward. The way manure built its complicated components, woody bits and lignocellulosic materials within it, alongside lots of ammonia (NH₃) can hamper the microbes that make H₂, meaning less H₂ overall [4,5]. Typically, simple fermentation processes struggle to fully break down the waste; therefore, they don't produce much H₂ while also leaving behind unwanted leftovers

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like certain volatile fatty acid (VFA). When nutrients are out of whack, especially too much C compared to nitrogen (N) in C/N ratio, it messes with microbes and hinders their ability to make H_2 [6,7]. Because of this, scientists have been working hard on bettering the process, prepping materials beforehand, and combining different systems so substrates break down more effectively while helping microbes work at their best for biohydrogen creation [8,9].

H_2 production gets boosted when linking two processes, dark fermentation (DF) alongside photo fermentation (PF). This pairing works because what is created during the first stage feeds the second, leading to better resource use also higher H_2 output. It's like one process sets up the next for success, making everything flow smoother [10]. Meanwhile, mixing livestock manure alongside things like crop leftovers or discarded food scraps proves a useful way to get nutrients right, lessen issues with NH_3 , then steady the whole operation [11]. These combined methods show real promise for building workable, large scale, eco-friendly systems that create biohydrogen from animal manure.

2. RESEARCH METHODOLOGY

2.1. Literature Identification and Selection

This study employed a narrative comparative review to comprehensively evaluate recent advances in biohydrogen production from animal manure. The review focused on feedstock characteristics, pretreatment technologies, fermentation pathways, co-digestion strategies, process optimization, and future industrial implementation. Scientific articles were retrieved from Scopus, Web of Science, ScienceDirect, and Google Scholar using combinations of keywords including "animal manure", "biohydrogen production", "dark fermentation", "photo fermentation", "integrated DF–PF", "pretreatment", and "co-digestion".

Literature selection followed predefined inclusion and exclusion criteria. Only peer-

reviewed articles published in English were considered. Although this review primarily emphasizes 143 studies published during the 2005–2026 period, earlier landmark publications were selectively included when necessary to establish the fundamental principles of biological hydrogen production. Eligible studies reported experimental findings or comprehensive analyses related to animal manure-based biohydrogen production, whereas studies outside this scope or lacking sufficient methodological information were excluded.

2.2. Data Synthesis and Comparative Analysis

The selected studies were synthesized using a qualitative comparative analysis. Information extracted from each article included feedstock characteristics, fermentation configuration, pretreatment method, operating parameters such as temperature, pH, hydraulic retention time (HRT), substrate concentration, and inoculum, biohydrogen yield, and production rate. These variables were comparatively evaluated to determine their influence on biohydrogen production performance.

The study compared the performance of DF, PF, and integrated DF–PF systems reported in previous research. The effects of pretreatment and co-digestion on substrate degradation, process stability, and hydrogen production were also evaluated. Comparative analysis was subsequently performed to identify relationships among manure characteristics, pretreatment strategies, fermentation pathways, operating conditions, and biohydrogen productivity rather than merely summarizing individual studies.

To further define the scope and research positioning of the present review, recent representative review articles related to biohydrogen production were comparatively evaluated according to their thematic focus, major contributions, and research coverage, as summarized in Table 1.

Table 1. Recent Review Articles Related to the Scope of the Present Review.

Main Focus	Key Strengths	Research Gap Addressed by the Present Review	Ref
Iron-based additives for biohydrogen and biomethane production	Comprehensive analysis of Fe-based materials, microbial responses, and economic aspects	Limited to iron-based additives; does not comprehensively evaluate manure feedstocks, pretreatment, or DF–PF integration	[12]
Emerging technologies (AI, nanotechnology, microbial engineering, TRL)	Integrates advanced technologies and future development roadmap	Broad biomass scope; lacks manure-specific analysis and comparison among livestock manures	[13]
Dark fermentation of agricultural residues	Up-to-date review of DF, pretreatment, and process optimization	Focuses only on DF and agricultural biomass; excludes PF, DF–PF, and animal manure	[14]
Lactate metabolism in dark fermentation	Detailed discussion of microbial metabolism and syntrophy	Focuses on metabolic pathways rather than feedstock, pretreatment, or process integration	[15]
Biohydrogen from various waste resources	Covers technologies, economics, policy, and applications	Animal manure is not the primary focus and comparative manure analysis is lacking	[2]
Biological and thermochemical conversion pathways	Comprehensive sustainability, LCA, TEA, and hybrid technology assessment	Broad biomass perspective without detailed evaluation of manure-specific characteristics and processes	[16]
General biohydrogen technologies	Covers production technologies, reactor design, and renewable integration	General technology review with limited emphasis on manure-based biohydrogen production	[17]

Unlike previous reviews that primarily focus on individual technologies, specific enhancement strategies, or broad biomass resources, the present review adopts a feedstock-oriented perspective by comprehensively evaluating animal manure as the primary substrate for sustainable

biohydrogen production. It integrates feedstock characteristics, pretreatment strategies, process optimization, fermentation pathways (DF, PF, and integrated DF–PF), co-digestion, and biohydrogen performance into a unified framework, thereby providing a

comprehensive framework for understanding and optimizing manure-based biohydrogen production systems.

2.3. Literature Coverage

To ensure that this review reflects current scientific developments while maintaining fundamental scientific context, the temporal distribution of references was also evaluated. Approximately 74% of the cited literature was published during 2016–2026 (106 references), including 67 references published between 2021–2026. Earlier studies were selectively incorporated only when they introduced fundamental fermentation mechanisms, microbial pathways, or pioneering biohydrogen production technologies.

3. RESULTS AND DISCUSSION

3.1. Biohydrogen Production Processes

3.1.1. Dark Fermentation (DF)

Microbes break down stuff like sugars, protein, and waste without sunlight, yielding H_2 . It works through natural processes involving varied chemical routes. Byproducts like vinegar, butyric acid, alcohol, alongside carbon dioxide (CO_2) because of competing reactions obtained too [18–20]. Microbes that don't require oxygen (O_2), like *Clostridium*, *Enterobacter*, *Bacillus*, thrive here. They employ hydrogenase alongside ferredoxin to move electrons, ultimately generating H_2 [21,22]. Compared with other biohydrogen production pathways, DF is currently the most extensively investigated technology for animal manure because it can directly utilize complex organic substrates without requiring light energy. Moreover, its relatively simple reactor configuration and lower operational costs make DF more feasible for large-scale waste treatment. However, the inherently low hydrogen conversion efficiency remains the major limitation driving the development of integrated fermentation systems.

Depending on surroundings and a microbe's internal state, they follow one of two primary methods either the more productive acetate (CH_3COO^-) route or the less efficient butyrate ($C_4H_7O_2^-$) route. The acetate

production pathway is generally more efficient and productive, with acetate generated through several metabolic routes, including carbohydrate fermentation. On the other hand, butyrate production pathway is generally less efficient than the acetate pathway, as butyrate is synthesized via routes involving butyrate kinase (buk) and butyryl-CoA:acetate CoA-transferase (but), primarily in *Clostridium* species that metabolize carbohydrates. While butyrate can serve as a substrate for H_2 production, it is less preferred than acetate because it yields lower current densities and coulombic efficiency in microbial systems [23,24]. Nevertheless, butyrate can positively influence certain bacteria, such as *Clostridium acetobutylicum*, by stimulating growth and metabolic activity [25]. In the context of DF using animal manure, the dominance of these pathways directly dictates the practical H_2 yield. The acetate-dominant pathway is highly preferred as it theoretically yields up to 4 mol H_2 /mol glucose, whereas the butyrate pathway is limited to 2 mol H_2 /mol glucose [26]. Although the acetate pathway theoretically provides twice the hydrogen yield of the butyrate pathway, acetate is not always the dominant metabolite in practical manure fermentation. This discrepancy indicates that theoretical stoichiometric yields cannot be directly translated into practical reactor performance because metabolic pathway selection is governed by microbial interactions and environmental conditions. Animal manure contains heterogeneous organic matter, indigenous microbial populations, and NH_3 , all of which influence metabolic flux distribution. Consequently, many studies report butyrate-type fermentation as the prevailing pathway because it is metabolically more stable under mixed-culture conditions despite producing lower theoretical biohydrogen yields. Therefore, maximizing theoretical biohydrogen yield alone is insufficient for practical manure fermentation, where process stability and microbial adaptability often become equally important performance indicators.

Appropriate operating conditions favor acetate-type fermentation and suppress competing microorganisms [27]. However, the optimum operating conditions vary considerably among studies because they depend on manure characteristics, inoculum source, reactor configuration, and microbial community structure. Detailed discussions regarding operational parameter optimization are presented in Section 3.2.2.

Complex materials break down into simpler building blocks along with useful organic acids which then feed bacteria that create H_2 . This process is crucial in DF systems where mixed microbial cultures decompose organic wastes to produce H_2 [28]. The quantity of H_2 gets made depends on those bacterial communities, how quickly they digest stuff, operational conditions, and what byproducts build up during the process; grasping these details is key to boosting H_2 creation [29,30]. Consequently, the considerable variation in hydrogen yields reported across manure-based studies can largely be attributed to differences in manure composition, NH_3 concentration, volatile solids (VS) content, indigenous microorganisms, reactor configurations, and pretreatment strategies. These interacting factors influence hydrolysis efficiency and metabolic flux distribution, emphasizing that substrate-specific optimization is more appropriate than applying universal operating conditions. After understanding the underlying process

and microbial dynamics in DF, it is essential to evaluate the benefits and drawbacks of this method compared to other biohydrogen producing pathways. To better understand how manure is converted into biohydrogen during dark fermentation, Figure 1 illustrates the two main metabolic routes involved in the process. These pathways differ significantly in the amount of biohydrogen they produce, making them essential to evaluate when optimizing biohydrogen generation. The following Table 2 summarizes the main advantages and disadvantages of DF in biohydrogen production.

As summarized in Table 2, the principal strengths of DF, including broad feedstock compatibility and operational simplicity, are counterbalanced by limitations related to H_2 yield, process stability, and commercialization. Consequently, current research has increasingly shifted toward integrating DF with pretreatment technologies, PF, anaerobic digestion, and bioelectrochemical systems to improve substrate conversion and overall biohydrogen recovery. Rather than relying solely on optimization of DF, future research should prioritize multidisciplinary strategies that integrate feedstock optimization, microbial community engineering, advanced reactor configurations, and downstream biohydrogen recovery to enhance the technical and economic feasibility of manure-based biohydrogen production.

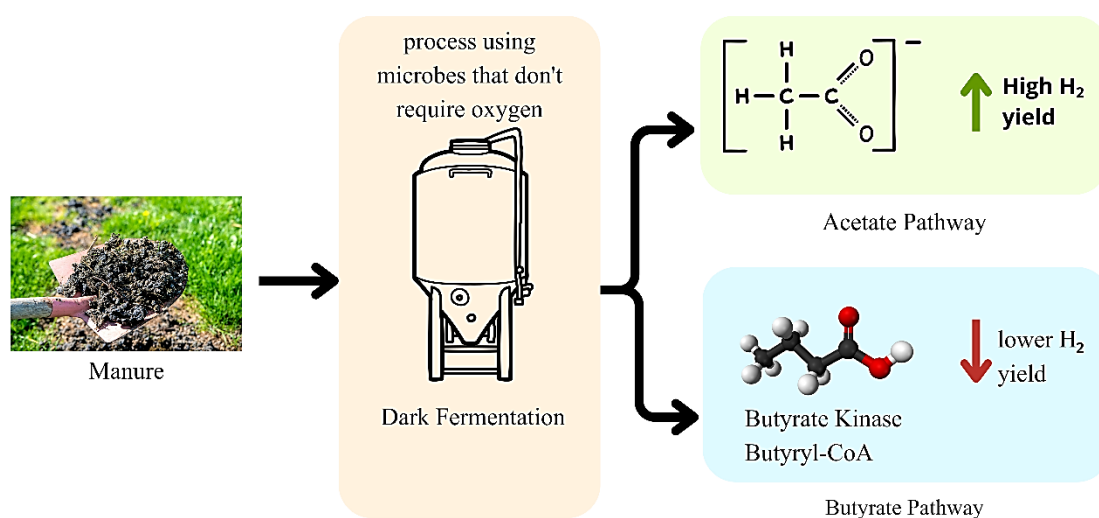


Figure 1. Metabolic Pathways of Dark Fermentation (DF) for Biohydrogen Production.

Table 2. Strength and Challenges of Dark Fermentation (DF) in Biohydrogen Generation.

Aspects	Strength	Current Challenge	Ref
Feedstock	Diverse livestock manure	Pretreatment required for complex substrates	[31]
H ₂ Production	High lab-scale yield	Lower yields during scale-up	[32,33]
Operation	Simple reactors; no light	Sensitive to pH, inhibitors, and microbial instability	[34]
Commercialization	Eco-friendly and integrable with waste-to-energy	Purification and economic viability remain challenging	[32]

3.1.2. Photo Fermentation (PF)

Some sunlight loving bacteria or purple non-sulfur (PNS) bacteria make H₂ without needing O₂. These include types called *Rhodobacter*, *Rhodopseudomonas*, *Rhodospirillum* which employ enzyme like nitrogenase also hydrogenase to pull protons apart, yielding H₂. Nitrogenase primarily responsible for H₂ production in PNS bacteria, while hydrogenase help cells maintain energy and redox balance, but also consume the H₂ produced depending on the type and conditions which led to decrease of biohydrogen [35,36]. Representative PNS bacteria include *Rhodobacter sphaeroides*, *Rhodopseudomonas palustris*, and *Rhodospirillum rubrum*, which differ in carbon substrate utilization, nitrogenase activity, and biohydrogen productivity. These physiological differences partly explain the variability in PF performance reported across different manure-based studies [37–39]. Among these, acetate, lactate (C₃H₅O₃⁻), and butyrate are the principal carbon sources supporting biohydrogen production during PF [40,41]. Compared with DF, PF offers superior substrate conversion efficiency because it utilizes organic acids generated during fermentation as electron donors for hydrogen production. However, its dependence on continuous illumination and photosynthetic metabolism generally results in lower biohydrogen production rates and more complex reactor operation, limiting large-scale implementation.

PF can generate more than 50 mL H₂/g-VS, with performance strongly influenced by light intensity (2000–4000 lux), feedstock properties, and nutrient conditions [42,43]. Compared with dark fermentation, PF generally provides lower production rates but higher substrate utilization efficiency. This trade-off arises because PF depends on photosynthetic metabolism, which proceeds more slowly than fermentative pathways but enables additional conversion of residual VFA into biohydrogen.

Under nitrogen (N₂) limited conditions, manure-based systems can achieve 16.4 mL H₂/L/h; however, maintaining such rates at large scale remains challenging because of illumination requirements, reactor complexity, and economic considerations [44,45]. Although N₂ limitation enhances nitrogenase mediated biohydrogen evolution, excessive nutrient limitation may also suppress bacterial growth, indicating that an appropriate balance between biomass formation and biohydrogen production is required.

Nevertheless, substantial variations in hydrogen production have been reported among manure-based studies because light penetration, VFA composition, nitrogen availability, and photobioreactor configuration directly influence nitrogenase activity and photosynthetic efficiency. Overall, PF represents an effective complementary pathway rather than a standalone alternative for manure-based biohydrogen production. Its ability to utilize

fermentation byproducts substantially improves substrate conversion efficiency, although practical implementation remains constrained by light availability, reactor design, and operating costs. These characteristics explain why PF is increasingly integrated with DF instead of being applied independently. Figure 2 summarizes the key mechanisms governing PF for manure-based biohydrogen production. Unlike DF, PF utilizes residual volatile fatty acids as carbon sources and is highly dependent on light availability and nitrogenase activity. The figure also highlights that operational parameters, particularly light intensity, nutrient availability, and reactor configuration, simultaneously influence hydrogen production efficiency and represent the major barriers to large-scale implementation. Table 3 below outlines the main advantages and disadvantages of PF in biohydrogen production.

As summarized in Table 3, PF provides superior substrate utilization and environmental benefits but remains constrained by low biohydrogen productivity, light dependency, and commercialization challenges. Consequently, current research increasingly focuses on integrating PF with DF to exploit the complementary advantages of both processes. Rather than optimizing PF as a standalone technology, future research should emphasize photobioreactor development, light management strategies, microbial engineering, and integrated fermentation systems to improve the technical and economic feasibility of manure-based biohydrogen production. These complementary characteristics have encouraged the development of integrated DF-PF systems, which are discussed in the following section.

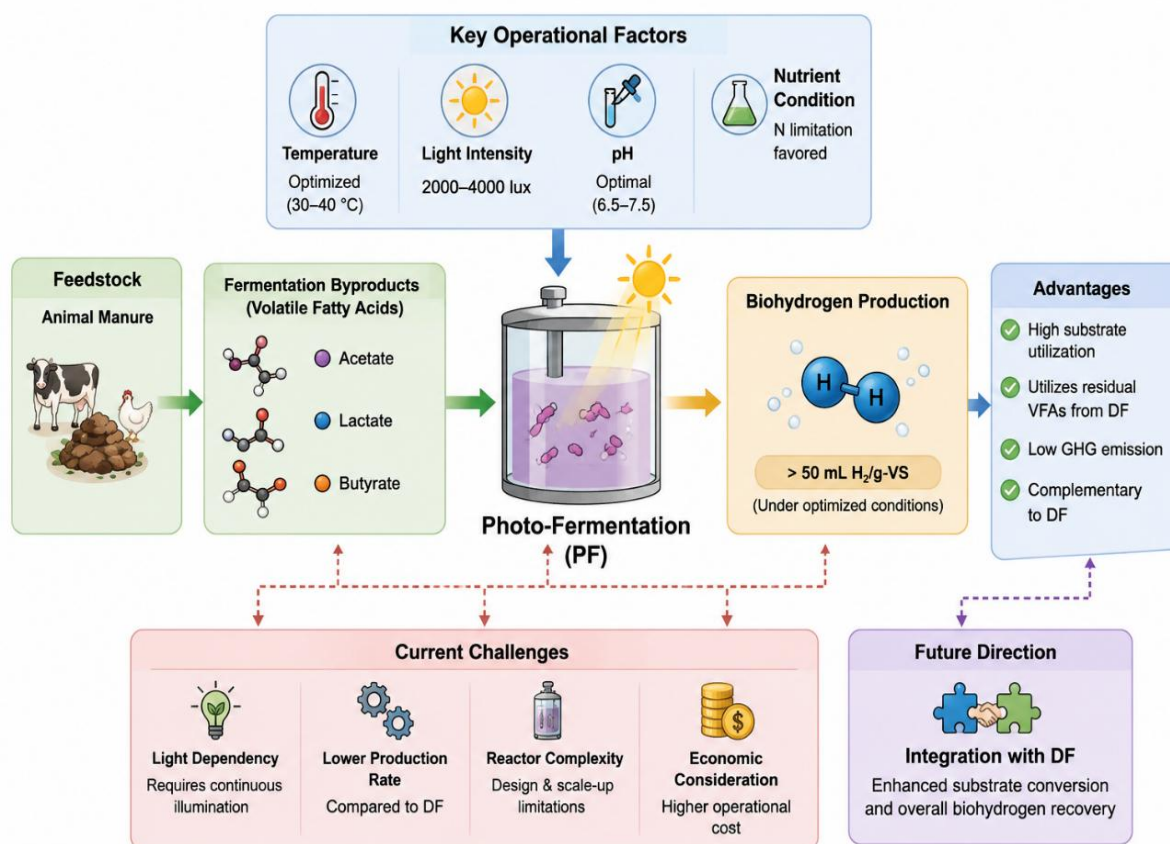


Figure 2. Summary of Key Mechanisms in Photo-Fermentation (PF).

Table 3. Strength and Challenge of Photo Fermentation (PF) in Biohydrogen Production.

Aspects	Strength	Current Challenge	Ref
Feedstock	Utilizes low-cost manure for waste valorizations	Variable composition and nutrient imbalance	[46–48]
H ₂ Production	Enhanced by nutrient supplementation and microbial consortia	Low H ₂ yield due to substrate complexity and microbial inhibition	[46–48]
Operation	Mild operating conditions	Light-dependent operation and process instability	[46–48]
Commercialization	Potential for integrated manure treatment and renewable energy recovery	Limited pilot-scale validation and cost-effective reactor design	[46–48]

3.1.3. Combined System (DF-PF) and Comparison of Processes

A clever process merges two types of bacteria, those thriving without light alongside those using sunlight, so nearly all waste breaks down, boosting H₂ production. Initially, fermentation in darkness transforms things like sugars and proteins into useful compounds, specifically VFA, alcohols, yet also organic acids. This method ensures the complete utilization of organic substrates, reducing chemical oxygen demand (COD) in the effluent by up to 90% [45,49,50]. What often builds up as waste in initial processing becomes fuel for specialized bacteria. Pairing dark and photo fermentation (DF-PF) cleverly cuts down on leftover gunk while also making more H₂ using sunlight and natural processes. DF produces biohydrogen through anaerobic degradation of carbohydrates without light, whereas PF utilizes light energy to convert fermentation metabolites into additional biohydrogen. They differ because one works through direct chemical reactions, while the other harnesses light to split water, creating H₂. Dividing things up lets different microbe groups thrive which some like heat and the others don't, during breakdown processes makes the whole thing work better [51–54]. Unlike standalone DF or PF, the integrated DF–PF system exploits the complementary metabolic characteristics of both processes, allowing residual fermentation products from

DF to be further converted into biohydrogen during PF.

The integrated DF–PF process generally improves substrate conversion efficiency and reduces inhibitory metabolite accumulation. Under optimized conditions, individual studies have reported biohydrogen increases of up to 134% compared with standalone systems [55]. However, such improvements should be interpreted cautiously because the reported enhancement strongly depends on feedstock characteristics, pretreatment strategy, VFA composition, reactor configuration, microbial community structure, and operating conditions. Consequently, similar performance cannot be universally expected across different manure types and fermentation systems.

H₂ production gets a real lift when DF-PF work together, squeezing more energy from the starting materials while being kinder to the environment. While DF is quick, it doesn't quite finish the job, frequently leaving some waste products. Consequently, PF takes over, converting these leftovers into additional H₂, ultimately increasing total output [55–57]. Linking the two systems of fermentation sequentially or simultaneously, almost doubles H₂ production compared to using just one system. The systems work well together naturally, so this method yields H₂ more cleanly and effectively [58,59]. The synergistic performance of DF–PF originates from the complementary metabolic functions of both systems rather than from simply

combining two fermentation stages. DF rapidly converts biodegradable carbohydrates into VFA, whereas PF recovers the remaining chemical energy by converting these metabolites into additional biohydrogen. This complementary relationship simultaneously improves substrate utilization, reduces residual organic matter, and minimizes carbon loss. Nevertheless, several challenges remain before integrated DF–PF can be commercially implemented. Process synchronization, stable microbial interactions, reactor integration, light distribution, and additional capital costs continue to limit industrial-scale application. Illustration in Figure 3 shows how DF-PF system process, beginning with substrate preparation and optimization, followed by DF system as the initial H_2 producing step, then PF as the subsequent stage to further enhance H_2 recovery. To better understand how the combined system enhances biohydrogen yield and efficiency, it is

essential to compare the operational features and outcomes of each process. The following Table 4 presents a comparative summary of DF, PF, and their combined system in terms of key parameters, performance, and practical aspects.

As summarized in Table 4, DF-PF combines the rapid biohydrogen production of DF with the superior substrate utilization efficiency of PF, resulting in higher overall biohydrogen recovery than either standalone process. However, this enhanced performance comes at the expense of greater operational complexity, requiring effective synchronization between fermentation stages and optimized reactor integration. Future research should therefore prioritize integrated reactor design, microbial consortium engineering, pilot-scale validation, and techno-economic assessment to bridge the gap between laboratory findings and industrial implementation of manure-based biohydrogen production.

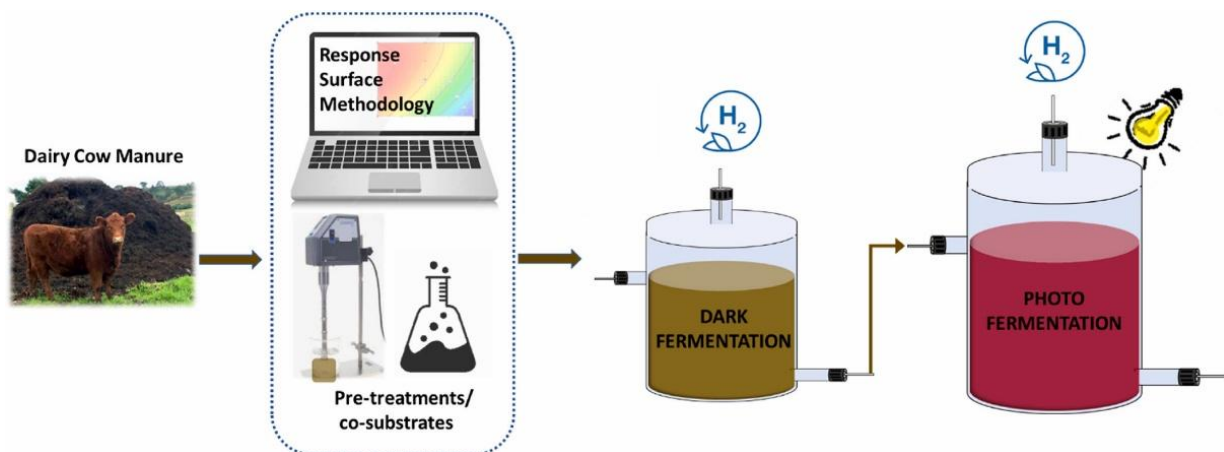


Figure 3. Combined System (DF-PF) of Biohydrogen Production Process [60].

Table 4. Comparison of DF, PF, and Combined System (DF-PF) in Biohydrogen Output.

Parameters	DF	PF	DF-PF	Ref
Carbon source	Carbohydrates/Sugars	VFA, organic acid	Sugars → VFAs	[61,62]
Energy source	Organic matter	Light	Organic matter + light	[61]
Microorganism	Anaerobic bacteria like <i>Clostridium</i> spp. and <i>Enterobacter</i> spp.	PNS bacteria	Sequential consortium	[57,61, 62]
Optimal parameters	Initial substrate concentration, hydraulic retention time (HRT) 6–24 h, pH 5.0–6.5, temperature mesophilic (30–40°C) and thermophilic (50–60°C)	Light intensity 3000–10000 lux (or LED 800–900 nm), C/N ratio 20–40, pH 6.5–7.5, temperature 20–40°C	Integration from both DF and PF	[57,61, 63]
H ₂ yield*	1.72 mol-H ₂ /mol glucose	4.16 mol-H ₂ /mol glucose	5.48 mol-H ₂ /mol glucose	[64]
Major strength	Fast biohydrogen production	High substrate utilization	Highest overall recovery	[61,62, 65]
Major limitation	VFA accumulation	Light dependency	Process integration complexity	[45,62, 63,65–67]
Industrial potential	Moderate	Low	High, but require optimization	[61,63, 66]

*Representative values reported under specific experimental conditions; actual yields vary considerably among feedstocks and operating conditions.

3.1.4. Relationship Between Anaerobic Digestion and Biohydrogen Fermentation

Anaerobic digestion and biohydrogen fermentation share the same initial biochemical pathways, namely hydrolysis, acidogenesis, and acetogenesis, during which complex organic matter is converted into soluble intermediates, VFAs, H₂, and CO₂ [3,68]. The major distinction lies in the final stage of the process. Conventional anaerobic digestion proceeds to methanogenesis, where methanogenic archaea consume H₂ and acetate to produce methane (CH₄), whereas biohydrogen fermentation intentionally

suppresses this stage to preserve H₂ as the primary end product [69,70]. This distinction explains why biohydrogen production generally requires stricter process control than conventional anaerobic digestion, as even limited methanogenic activity can substantially reduce hydrogen recovery. Although methanogen inhibition is essential for maximizing biohydrogen recovery, maintaining stable hydrogen-producing microbial communities remains challenging because operational conditions that suppress methanogens may also affect other functional microorganisms. Therefore, selective control of pH, temperature, HRT, inoculum

pretreatment, and microbial competition has become a critical strategy for maximizing biohydrogen production while minimizing CH_4 formation in manure-based systems [71,72]. Accordingly, the following section discusses the principal process optimization strategies, including pretreatment, operational parameter optimization, and co-digestion approaches, that have been developed to enhance manure-based biohydrogen production.

3.2. Process Optimization Strategies

3.2.1. Physical, Chemical, and Biological Pretreatment of Animal Manure

Animal manure is a heterogeneous substrate containing lignocellulose, proteins, lipids, and mineral components that limit direct microbial degradation. Consequently, pretreatment has become one of the most important optimization strategies because it enhances substrate accessibility, accelerates hydrolysis, and improves the availability of fermentable compounds for biohydrogen-producing microorganisms.

To help bacteria make H_2 , animal waste needs some initial work. Untreated cow, pig, or chicken manure usually has 25–45% of tough plant fibres alongside 15–25% protein. These materials don't break down easily by themselves. Preheating waste between 100–121°C for 1 h, autoclaving method which involves heating at high pressure, breaking it apart using sound waves at 20–40 kHz, or grinding it down until pieces are less than <1 mm boost readily available chemicals by 20–45%, making breakdown simpler [73–76]. For example, warming pig manure helps produce more H_2 , increasing output reached 102.1 mL- H_2 /h, because it dissolves better, though doesn't create many hindering substances. Other research shows that hydrothermal treatment of pig manure from 150°C also increased gas yields [77,78]. Physical pretreatment primarily improves biohydrogen production by increasing surface area, disrupting lignocellulosic structures, and enhancing solubilization of organic matter. However, increasing pretreatment severity does not always

improve biohydrogen production. Excessive thermal treatment may generate inhibitory compounds and increase energy consumption, indicating that pretreatment conditions should be optimized according to manure characteristics rather than maximized.

To break down organic waste efficiently with minimal energy, chemical methods work well alongside biological ones. Adding either a little sodium hydroxide (NaOH) or dilute sulfuric acid ($\text{H}_2\text{SO}_{4(\text{aq})}$) to animal manure increases available sugars which leads to considerably more H_2 generation. NaOH can improve electron transfer capacity and structural properties, also break down manure fibres and making sugars more accessible for microbial digestion [79,80]. $\text{H}_2\text{SO}_{4(\text{aq})}$ is effective in hydrolysing manure to release sugars and significantly increase the yield of fermentable sugars, which are essential for H_2 production, it also can reduce NH_3 and CH_4 emissions [80,81]. Alkaline pretreatment is generally more effective for lignin disruption, whereas dilute acid pretreatment preferentially hydrolyses hemicellulose. Therefore, alkaline and acid pretreatments should be selected according to manure composition and process objectives rather than being considered universally applicable.

Meanwhile, employing certain fungi or enzymes diminishes tough lignin components while simultaneously raising levels of sugars ready for fermentation; crucially, these processes don't create unwanted pollution. Fungal pretreatments involve the use of lignin-degrading fungi like white rot fungi which produce ligninolytic enzymes such as *laccase*, *manganese*, *peroxidase* to degrade lignin and enhance the digestibility of cellulose. The fungi method is not just environmentally friendly, but also energy efficient and suitable for large scale application [82,83]. Enzymatic pretreatment involves the use of specific enzymes to hydrolyse cellulose and hemicellulose into fermentable sugars [84,85]. Better H_2 output comes from pairing initial enzymatic hydrolysis of pretreated source with

fermentation in a single step, either one after the other or happening simultaneously [83]. Although biological pretreatment requires longer processing times, it consumes substantially less energy and produces fewer inhibitory compounds than thermal or chemical methods, making it attractive for sustainable large-scale applications. Pretreatment for H_2 production from animal manure is strongly dependent on feedstock characteristics, treatment severity, and fermentation conditions. The main pretreatment strategies are comparatively evaluated in Table 5.

Taken together, the quantitative evidence indicates that pretreatment severity and H_2 enhancement do not necessarily translate into superior process performance. Thermal treatment of swine manure increased H_2 productivity by 77.4%, while the combined H_2O_2 -ultrasound treatment of dairy cow manure achieved a larger 125% improvement but required substantial ultrasonic energy input.

Therefore, pretreatment selection should be feedstock-specific and based on the balance between H_2 enhancement and process burden, rather than on H_2 yield alone. Thermal treatment appears particularly

promising for swine manure, whereas acidification can provide substantial H_2 production from dairy manure but requires careful control of pH and treatment severity. Alkaline treatment may be advantageous where lignocellulosic recalcitrance is the principal limitation, while biological approaches offer the lowest chemical burden but remain constrained by process complexity. Combined pretreatments provide substantial enhancement potential, but their higher energy and operational requirements make net hydrogen-energy recovery and process integration essential criteria for assessing their practical scalability. Consequently, integrated pretreatment strategies are increasingly being investigated to balance biohydrogen yield with process economics and environmental performance. Figure 4 summarizes the general pretreatment workflow for animal manure prior to biohydrogen fermentation. Following initial conditioning and homogenization, physical, chemical, and biological pretreatments are applied to overcome different structural barriers within manure, ultimately converting complex organic matter into more readily degradable compounds for microbial utilization.

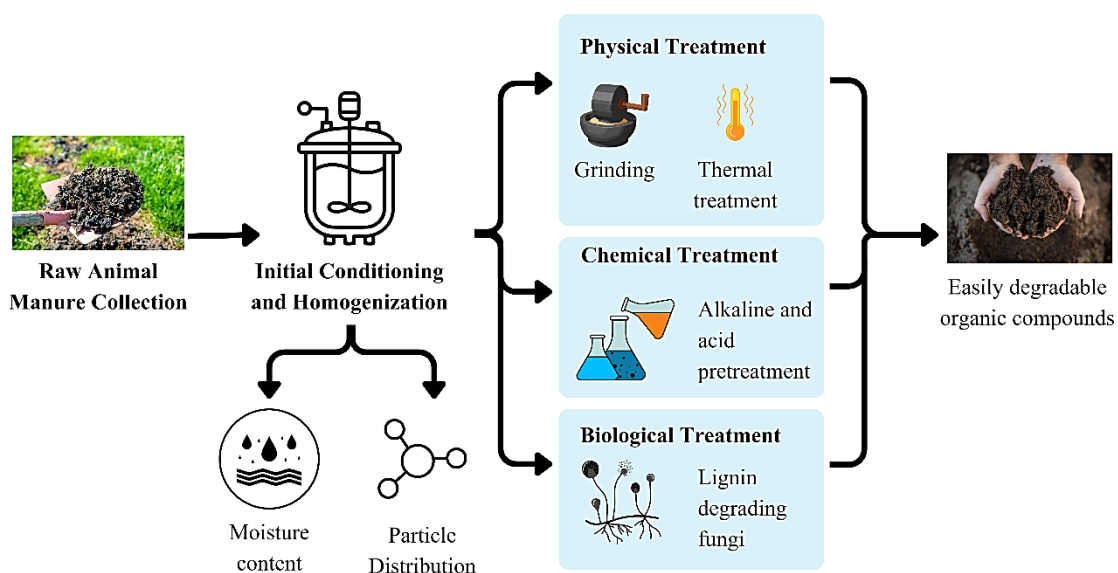


Figure 4. Physical, Chemical, and Biological Pretreatment of Animal Manure.

Table 5. Comparative evaluation of pretreatment strategies for biohydrogen production from animal manure.

Category	Pretreatment				
	Thermal	Alkaline	Acid	Biological	Combined
H ₂ Yield Improvement	Increased by 77.4% (from 20.6 to 36.6 mL H ₂ /g TS-added) at 80°C for 30 min with swine manure	Increased by 6.8% (from 13.1 to 14.0 mL H ₂ /g TVS) using 0.2% NaOH for 30 min with dairy manure	Increased by 900% (from 9.7 to 97 mL H ₂ /g solid waste) using 2.5% oxalic acid at 135°C with dairy cow solid waste	No sufficiently verified quantitative improvement was identified for biological pretreatment alone using animal manure	Increased by 125% (from 22.75 to 51.25 mL/L) using combined H ₂ O ₂ + ultrasound pretreatment with dairy cow manure
Energy Requirement	Moderate–high	Potentially low for ambient temperature	Potentially low for ambient temperature	Low for pretreatment, although specialized thermophilic conditions may increase process energy demand	High–very high; the optimized treatment required
Chemical Consumption	No chemical reagent is required	Moderate–high; followed by pH neutralization.	Moderate–high; followed by pH neutralization.	No chemical reagent is required	Moderate, depends on the pretreatment type
Inhibitor	Moderate, excessive VFA accumulation can inhibit H ₂ production	Low–moderate, excessive alkalinity can interfere with downstream fermentation	Moderate–high, can cause degradation of fermentable sugars	Biological inhibition can arise from substrate composition and fermentation metabolites	Moderate; depends on the pretreatment type
Operational Complexity	Relatively simple	Moderate	Moderate–high	High, specialized microorganisms increase requirements	High, multiple treatment variables must be controlled simultaneously
Scalability	High with appropriate heat recovery	Moderate-high, but chemical handling must be addressed	Moderate, but chemical handling increases requirements	Moderate–low, maintaining specialized cultures remain challenging	Moderate, but high energy input can constrain economic
Ref	[86]	[87]	[88]	[89]	[76]

3.2.2. Optimization of Operational Parameters

Operational parameter optimization is essential because biohydrogen production is governed by complex interactions between microbial metabolism, substrate characteristics, and reactor operation. Unlike pretreatment, which improves substrate

accessibility, operational optimization aims to maximize hydrogen-producing microbial activity while suppressing competing metabolic pathways, particularly methanogenesis. Factors like acidity, warmth, HRT, also the amount of starting material each affect microbes making H₂, even power tools. A little acidity (around pH

5.0–6.5) helps H_2 makers thrive yet keeps hydrogen consuming microorganisms [88,90]. Some studies also report optimal biohydrogen yields at neutral pH levels (around 7.0). This suggests that the optimal pH can vary depending on other conditions and the specific microbial consortia used [91,92]. The reported differences mainly arise from variations in manure composition, inoculum source, reactor configuration, and microbial community structure. Therefore, pH should be optimized for each fermentation system rather than adopting a universal optimum value.

Temperature is another critical parameter, microbes thrive when comfortably warm at mesophilic range around 35–40 °C usually works well for overall growth. However, thermophilic temperatures like >50 °C really help break things down, boosting gas production [91,93]. Although thermophilic operation generally accelerates hydrolysis and pathogen reduction, it also requires higher energy input and may reduce process stability. Consequently, mesophilic operation is often preferred when balancing H_2 productivity with operational costs.

Biohydrogen production really benefits from getting pH and temperature right, yet also needs careful attention paid to HRT, substrate concentration, and the composition of the microbial community. The optimal HRT reported in various studies often diverges due to complex interactions between reactor configuration, substrate characteristics, inoculum source, pH, and organic loading rate (OLR). For instance, a short HRT of 12–25 h is frequently optimal in continuous systems treating simple or soluble sugars; this rapid turnover suppresses slow-growing methanogens through cell washout while selecting for fast-growing, hydrogen-producing acidogens. Conversely, a longer HRT of 72 h coupled with a high OLR of up to 50 g COD/L can significantly enhance the biohydrogen production rate when dealing with complex, particulate substrates or high-solid organic wastes [90,94]. In these scenarios, the extended HRT is essential to provide sufficient contact for the preliminary

hydrolytic phase to break down complex polymers, preventing VFA accumulation that would otherwise inhibit microbial activity at high OLR [95]. Therefore, HRT should be optimized together with OLR and substrate biodegradability because these parameters are closely interdependent.

Excessive substrate loading may lead to VFA accumulation, pH reduction, and microbial inhibition; whereas insufficient substrate loading limits biohydrogen productivity [96]. A smart microbe-to-food ratio or called substrate-to-inoculum (S/I) ratio keeps things fermenting actively, avoiding issues where excess food stops the process. An optimal S/I ratio of 1:3 was found to support diverse microbial communities and enhance biohydrogen production [97]. Consequently, substrate concentration should be adjusted according to the biodegradability of the manure to avoid substrate inhibition or nutrient limitation.

Hydraulic flow rate also influences biohydrogen production by affecting HRT, microbial retention, and substrate contact time in continuous reactors. For example, a flow rate of 8 mL/min resulted in higher biohydrogen production, but lower conversion efficiency compared to lower flow rates [98,99]. Essentially, optimization of operational parameters requires balancing microbial activity, substrate degradation, and reactor performance rather than maximizing individual variables, because all operating parameters are closely interconnected.

3.2.3. Co-Digestion Approach for Fermentative Biohydrogen Production

Co-digestion has emerged as an effective strategy for improving biohydrogen production because animal manure alone often exhibits nutritional imbalance, high NH_3 content, and limited readily biodegradable carbon. By combining manure with complementary organic substrates, co-digestion improves substrate characteristics and creates a more favourable environment for biohydrogen-producing microorganisms. Mixing farm manure alongside things like

leftover crops, food scraps, or factory discards helps create a better mix of nutrients while also making more H_2 . This happens during anaerobic digestion, specifically when stuff first starts breaking down through fermentation [3,100,101].

Bacteria get to work on carbs, turning them into useful stuff, gases like those found in vinegar, alongside CO_2 and H_2 . Getting the food mix just right, specifically how C/N ratio there is, keeps things running smoothly. It avoids buildup that could slow down bacteria, therefore helping them consistently make H_2 . Low C/N ratios can lead to NH_3 inhibition, which hampers the degradation of organic matter and inhibits methanogens, thus reducing H_2 production. Excessively high C/N ratios can also be problematic, for instance, a C/N ratio of 300 in corn straw led to serious inhibition due to VFA accumulation [102,103]. Therefore, optimizing the C/N ratio is more important than simply increasing carbon or nitrogen content because nutrient balance directly

regulates microbial metabolism, VFA formation, and overall process stability.

Besides nutrient balancing, working together with different materials helps tiny organisms collaborate, boosting how well they break things down versus doing it alone. Adding stuff loaded with C gives a quick energy boost to microbes making H_2 while dialling back those creating CH_4 [104]. A smoother process happens because of increased storage plus less interference from hindering substances. Getting the right mix of materials, controlling how long things stay within the system, then managing the amount of waste added are key to consistently making lots of H_2 via co-digestion. Illustration in Figure 5 summarizes the general concept of anaerobic co-digestion for manure-based biohydrogen production. The schematic highlights how the addition of complementary co-substrates improves nutrient balance, particularly the C/N ratio, promotes microbial synergy, and ultimately enhances fermentative biohydrogen production.

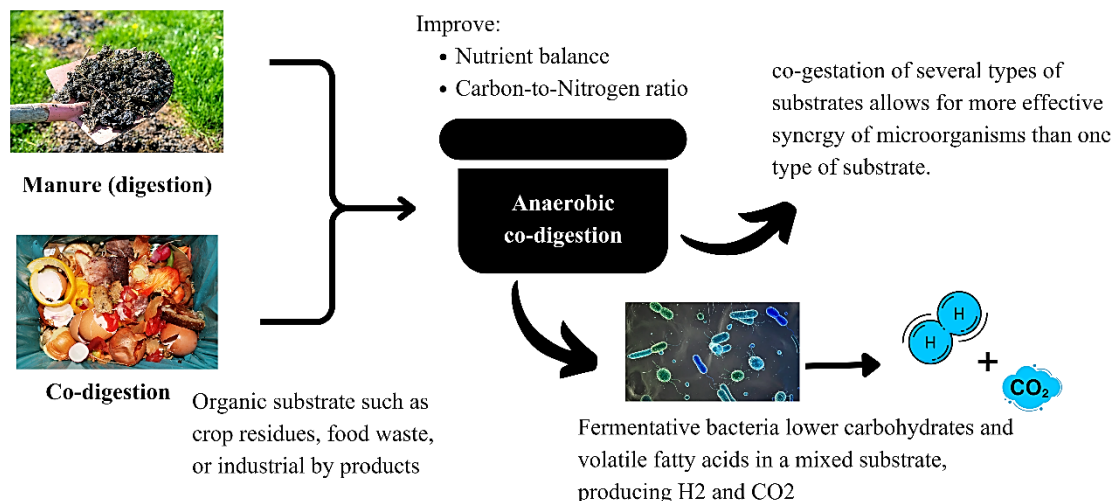


Figure 5. Anaerobic Co-Digestion Pathway for Enhanced Biohydrogen Production.

3.3. Feedstock Variation and Biohydrogen Yield

3.3.1. Overview of Animal Manure as Feedstock

Animal manure represents one of the most abundant organic feedstocks for fermentative biohydrogen production owing to its continuous availability from livestock

farming and its substantial organic matter content, including carbohydrates, proteins, lipids, and lignocellulosic materials [105–107]. However, its composition differs considerably among livestock species, resulting in distinct fermentation characteristics and biohydrogen production performance [48,108,109].

These compositional differences are primarily associated with animal diet, digestive physiology, manure handling practices, and storage conditions. Manure from ruminants, such as cattle and buffalo, generally contains higher lignocellulosic fiber fractions because plant biomass is only partially degraded during digestion. In contrast, pig and poultry manure typically contain greater proportions of proteins and readily biodegradable organic matter, leading to different C/N ratios, NH_3 generation, and microbial metabolic responses during fermentation [110–113]. Knowing different manure type, adjusting preparation techniques alongside processing could improve H_2 from biological sources while helping manure systems endure.

3.3.2. Comparative Analysis Among Feedstock Types

Reported biohydrogen yields from animal manure vary considerably because feedstock composition, pretreatment strategy, fermentation pathway, and reactor operation differ substantially among studies. Consequently, direct comparison of biohydrogen performance should consider the experimental conditions rather than yield values alone [114]. Among the reported livestock manures, pig manure generally exhibits relatively high biohydrogen yields because its balanced C/N ratio and higher fraction of readily biodegradable organic matter facilitate rapid microbial conversion [78]. Conversely, chicken manure often contains relatively high nitrogen concentrations, which may result in NH_3 accumulation during fermentation. NH_3 concentrations above 9.8 g/L have been reported to inhibit hydrogen-producing

microorganisms and reduce biohydrogen production [115]. Overall, the available studies indicate that biohydrogen performance cannot be attributed solely to manure type. Pretreatment method, reactor configuration, microbial consortium, and operating conditions frequently exert effects comparable to, or even greater than, intrinsic feedstock composition. Therefore, comparative evaluation should consider both feedstock characteristics and process configuration. Table 6 summarizes representative studies on different livestock manures, including fermentation pathway, pretreatment strategy, operating conditions, and biohydrogen performance.

The available studies collectively demonstrate that differences in biohydrogen yield cannot be attributed solely to the type of animal manure. Instead, biohydrogen performance results from complex interactions among feedstock composition, pretreatment strategy, microbial activity, reactor configuration, and operating conditions. Therefore, future research should prioritize integrated optimization approaches rather than focusing on individual factors independently. To further elucidate these interactions, cattle, swine, poultry, and mixed manure can be compared according to their major physicochemical and microbiological characteristics. These characteristics determine the principal process limitation of each feedstock and consequently influence the selection of pretreatment and fermentation pathway. Table 7 therefore summarizes the relationship between feedstock properties, recommended pretreatment, and suitable fermentation configuration.

Table 6. Comparative Performance of Different Animal Manure Feedstocks for Biohydrogen Production.

Feedstock	Fermentation Systems	Pretreatment	Condition Operation	H ₂ Yield	Production Rate	Ref
Cow manure + hydrogen peroxide (H ₂ O ₂)	DF-PF	-	H ₂ O ₂ 0.0015–0.06 g/g-TS, sonication times 0–20 min	82.08 mL/g-VS	-	[76]
Cow manure + cheesy way	DF-PF	-	Incubated at 35 °C, SI ratio 5, CM: CW ratio 8:2, then rotation speed 250 rpm at 25 °C and under 4000 lux	263.13 mL/g-VS	-	[76]
Dairy solid cow waste + oxalic acid (C ₂ H ₂ O ₄)	DF	Chemical pretreatment with 2.5% C ₂ H ₂ O ₄ for 30 min	35 °C in batch reactor, pH 6.8, substrate conc. 100 g-VS/L	97 mL/g-VS	-	[88]
Dairy solid cow waste + endo nutrient	DF	Nutrient pretreatment with ratio 1:3	37 °C in cyclic activated sludge bed reactor (CASBR), pH 5.5, COD 30±2.8 g/L, HRT 12 h	-	150.59±35.7 mL/L/day with average H ₂ concentration 41.01%	[88]
Dairy manure	DF	Acidification pretreatment	Anaerobic fermentation, pH 5	31.5 mL H ₂ /g-VS	-	[116]
Cow manure	DF	-	With <i>Caldicellulosiruptor bescii</i>	82.5 mL H ₂ /g-VS	-	[89]
Cattle manure + food waste (FW)	DF	-	47– 51% FW:rest manure, mesophilic, semi-continuous; 76–86 g/L; HRT 2 d	>30 mL H ₂ /g-VS	>1.0 L/L.d	[94]
Cattle manure + chicken manure + corn silage + olive pomace	DF	-	Co-digestion, anaerobic, manure:FW = 6:4, pH 6.5	50.4 mL H ₂ /g-VS; Peak H ₂ 436±10 mL	-	[117]
Chicken manure slurry	DF	-	Continuous hydrogenic fermentation	-	1383 mL/L.d	[118]
Chicken manure + FW	DF-PF	-	Batch anaerobic fermentation 2-stage	15.5–57.5 mL H ₂ /g-VS	-	[119]
Buffalo manure + cheese whey	DF	-	pH 4.8–5.0; thermophilic	152 mL H ₂ /g-VS	215 mL H ₂ /L/d	[120]
Horse manure + Sodium	DF	-	Supercritical water gasification (400–	129.9 mL H ₂ /g-VS	-	[121]

Feedstock	Fermentation Systems	Pretreatment	Condition Operation	H ₂ Yield	Production Rate	Ref
Bicarbonate (Na ₂ CO ₃)			600°C, 23–25 MPa, 2 wt% Na ₂ CO ₃)			
Pig manure + FW	DF	-	pH 5.5–6.2, HRT 1 d, mesophilic, PM:FW = 8:2	275.6 mL H ₂ /g VS	1.32 L/L.d	[122]
Pig manure + fruit/veg waste	DF-PF	-	Two-stage mesophilic fermentation	15.5–57.5 mL H ₂ /g-VS	-	[123]

Table 7. Comparative characteristics and biohydrogen production suitability of different animal manure feedstocks

Characteristics	Feedstock				Ref
	Cattle/Cow	Swine/Pig	Poultry	Mixed	
C/N ratio	15–26	6–14	5–15	Mixture-dependent; no universal C/N value can be assigned	[124,125]
NH ₃	Representative free-ammonia nitrogen of 1.5 g/kg	Representative free-ammonia nitrogen of 4.5 g/kg	Representative total ammonia nitrogen (TAN) 4.97 g/kg	Mixture-dependent; blending may dilute the NH ₃ load	[124,126,127]
Lignocellulose	Approximately 50% of dry weight can be lignocellulosic, particularly when fibrous feed is present	Moderate and variable, lower fibrous content than cattle/cow manure	Highly variable due to litter/bedding composition, with neutral detergent fibre (NDF) 38.6–58.5%	Mixture-dependent, determined by the proportion manure and any additional lignocellulosic substrate	[128–130]
VS	75–95% in the comparative characterization	78–80% in the comparative characterization	74.7–87.3% in comparative characterization	Mixture-dependent; need to specify the mixing ratio	[124,130,131]
Moisture content	Highly variable with manure handling and bedding, reported 70.7%	Commonly handled as slurry, so a universal moisture value is inappropriate	Strongly dependent on litter and handling, fresh poultry litter 13.6–22.6%	Mixture-dependent, particularly when solid and slurry manures are combined	[124,128,130,131]
Buffering capacity	Representative alkalinity of 32.7 g CaCO ₃ /kg	Representative alkalinity of 13.8 g CaCO ₃ /kg	Livestock manure has substantial buffering capacity, but a sufficiently consistent quantitative	Mixture-dependent according to the alkalinity of the component manures	[126,132]

Characteristics	Feedstock				Ref
	Cattle/Cow	Swine/Pig	Poultry	Mixed	
Indigenous microbial communities	Comparative 16S-rDNA profiling showed a distinct microbial community and rapid initial AD phase	Microbiome profiling identified a distinct strong hydrogenotrophic-methanogenic phase during AD	Microbiome profiling showed had a distinct microbial profile and that its AD phases	Increased diversity in mixed manure should not be assumed without direct microbiome analysis	[133]
Suitable pretreatment	Physical or mild alkaline is appropriate when lignocellulosic hydrolysis is limiting	Mild thermal or alkaline may be used when hydrolysis is limiting; however, C/N adjustment through co-substrate addition when N limitation dominates	Mild pretreatment or C/N adjustments preferable when NH ₃ is the dominant constraint	Depending on the dominant limitation after blending; co-digestion itself may correct C/N imbalance	[89,124,127, 131]
Suitable fermentation pathway	DF is generally most suitable, PF is less suitable as a standalone pathway, and DF–PF is preferable when sufficient organic acids are available	Same as left	Same as left	Same as left	[76,122,134]

The physicochemical ranges presented in Table 7 are representative values rather than fixed specifications for each manure type because manure composition varies with animal diet, age, housing/bedding, water addition, storage, and sampling conditions. Overall, cattle manure is primarily limited by lignocellulosic recalcitrance, whereas swine and poultry manure are more strongly affected by low C/N ratios and NH₃-related inhibition. Accordingly, pretreatment and fermentation strategies should be selected according to the dominant feedstock limitation. Hydrolysis-oriented pretreatment is more relevant for fibrous substrates, while C/N and NH₃ management become increasingly important for nitrogen-rich manure. These differences highlight the need for feedstock-specific process optimization to balance substrate accessibility, microbial activity, and hydrogen productivity.

3.4. Prospects and Research Directions

Turning manure into biohydrogen could improve with a two-step process, first fermenting in the dark, subsequently with light. Such pairings frequently yield 80.66% greater H₂ volumes when compared to basic approaches, this finding from a dedicated study optimizing sequential DF-PF integration, rather than a universal average [10,135]. In broader practice, the consistency of this yield improvement varies significantly depending on the manure type and specific operating conditions. For instance, liquid dairy or swine manure, which contains higher concentrations of VFAs like acetate and butyrate after the DF stage, typically shows more robust and consistent H₂ increments during subsequent PF. Conversely, solid or poultry manure rich in NH₃ can exhibit lower or less consistent improvements due to NH₃ toxicity inhibiting the nitrogenase enzyme of photosynthetic bacteria. Furthermore, maintaining strict operational control such as

optimizing the light intensity, adjusting the C/N ratio, and neutralizing the effluent pH between the dark and light stages is highly critical to reliably replicate such high-efficiency gains on a larger scale [136,137]. Tweaking microbes holds real promise for boosting biohydrogen output. Genetic modifications in bacteria, such as *Escherichia coli* and *Enterobacter asburiae*, have shown significant increases in H₂ production. For instance, manipulating the Formate Hydrogen Lyase (FHL) system by overexpressing the *fhlA* gene and deleting H₂-consuming hydrogenases can lead to substantial increases in H₂ yield, up to 65% [138,139]. Microbial consortia are effective in breaking down complex biopolymers found in organic waste, such as animal manure. These consortia can degrade recalcitrant substrates like lignocellulose, which are otherwise difficult to process. This degradation process is facilitated by the division of labor among different microbial species, including bacteria and fungi, which produce various enzymes to break down the substrates [140,141]. Because these living systems are customizable, work well with various manures, offering adaptable methods for many waste sources.

Looking ahead, figuring out if this works on a large scale alongside protecting the environment is key. Studies suggest making biohydrogen gas from farm animal waste could run about \$1.17–7.61/kg-H₂, potentially yielding roughly 1 ton/day at middle sized plants [142]. Biohydrogen from manure could remove C from the atmosphere, potentially up to 9 kg-CO₂ equivalent 1 kg-H₂ produced, though this varies based on what the manure contains alongside how it's processed. Environmental benefits of biohydrogen production include reduced CH₄ and nitrous oxide (N₂O) emissions [143]. Despite these promising prospects, further advances require integrated pilot-scale demonstration, reactor optimization, life cycle assessment (LCA), and techno-economic analysis (TEA) to establish the long-term feasibility and competitiveness of manure-based

biohydrogen production within future circular bioeconomy and waste-to-energy systems.

4. CONCLUSION

Biohydrogen production from animal manure represents a promising waste-to-energy strategy that simultaneously addresses renewable energy generation and livestock waste management. This review demonstrates that biohydrogen performance is governed not by a single factor but by the interaction among feedstock characteristics, pretreatment, operational optimization, and process configuration. DF remains the most mature technology because of its operational simplicity and broad substrate compatibility, whereas PF offers superior substrate conversion by utilizing residual VFAs. Their integration (DF-PF) has emerged as the most promising approach, with individual studies reporting biohydrogen improvements of up to 134%, while pretreatment strategies have increased hydrogen production rates to 102.1 mL H₂/h and biohydrogen yields exceeding 275.6 mL H₂/g-VS under specific operating conditions.

Future progress should therefore shift from optimizing individual process components toward developing integrated biohydrogen production systems that combine appropriate pretreatment, optimized DF-PF configurations, and co-digestion strategies. Equally important are pilot-scale validation, TEA, and LCE to bridge the gap between laboratory research and industrial implementation. Such multidisciplinary integration will be essential for improving the technical feasibility, economic competitiveness, and environmental sustainability of manure-based biohydrogen production, thereby supporting its future role in circular bioeconomy and low-carbon energy systems.

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AUTHOR CONTRIBUTIONS

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DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES

During the preparation of this manuscript, the authors used Grammarly to improve the grammar and readability of the manuscript. The authors also used Scopus AI and connected papers to assist in identifying and exploring relevant literatures. All references suggested by these tools were independently screened and verified by the authors against the inclusion criteria of this review. After using these tools, the authors reviewed and edited the content as necessary and take full responsibility for the content of the published article.

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