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Review of Biogas Production and Biomethane Potential of Fish Waste

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Abstract **– The increasing volumes of fish waste generated by South Africa's fishing and aquaculture industries create environmental challenges while offering potential avenues for renewable energy generation. The current energy mix in South Africa is primarily dependent on coal, while renewable sources represent only a minor fraction of the total supply. This systematic review evaluates the potential of fish waste for biogas and biomethane production within the context of South Africa's Just Energy Transition. A total of 39 studies were analysed for biogas yield, methane content, and operational parameters. Results indicate that fish waste is a viable substrate, with co-digestion often improving yields, though findings are inconsistent. Extreme heterogeneity (I^2 = 100 %) limits pooled interpretation, highlighting the need for standardized methodologies. Environmental and economic assessments were largely descriptive, underscoring gaps in sustainability metrics. Future research should adopt uniform reporting standards and integrate life-cycle and cost-benefit analyses to inform policy and practice.**

Keywords **– Anaerobic digestion; biogas; biomethane; co-digestion; fish waste; renewable energy; substrates; yield.**

1. INTRODUCTION

South Africa has declared its dedication to the Just Energy Transition to evolve into a low-carbon economy and a climate-resilient society [1]. South Africa is actively pursuing a strategy to diversify its energy mix to enhance energy security while reducing carbon dioxide (CO_2) emissions. The current energy mix comprises 80.1 % coal, 4.6 % nuclear, and 13.7 % renewable energy. Within the renewable sector, 7.3 % is attributed to sources excluding hydro, while diesel and natural gas account for the remaining 1.6 % [2]. Enhancing renewable energy in South Africa would prompt an exploration of alternative systems such as biogas. Despite South Africa's growing interest in biogas, the potential of fish waste remains underexplored compared to agricultural residues. South Africa's National Waste Management Strategy 2020 aims to reduce landfill waste by 70 % by 2035 through reuse, recycling, recovery, and alternative waste treatment [3]. In 2019, the country produced 452,900 metric tons of fish and aquaculture, with marine fish accounting for 96 %, molluscs for 3 %, and crustaceans for 0.4 % [5]. Fish waste is a diverse type of waste, abundant in proteins and lipid compounds [6]. The insufficient use of fish waste presents environmental challenges, primarily stemming from the health hazards and pollution associated with current disposal

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methods [7]. The anaerobic digestion process applied to fish waste (FW) facilitates the transformation of organic matter into biogas, thereby minimizing landfill usage and producing clean energy [8]. Biogas presents significant potential and aligns well with the various challenges confronting South Africa's energy sector. South Africa predominantly obtains biogas from food, agriculture, and agro-processing waste [9]. Most anaerobic digesters, precisely 90 %, are categorized as small-scale, with sizes measuring less than 10 m^3. Currently, there are fewer than 300 registered units [9]. Biogas has a range of uses, including renewable electricity generation, heating, and gas production [10]. There is an opportunity to utilize the frequently discarded or underutilized fish waste from aquaculture operations for biogas production [11].

This review methodically evaluates the potential of fish waste for biogas and biomethane production in South Africa by analysing existing studies on the anaerobic digestion of fish waste and examining the ecological and energy benefits of utilizing fish waste for renewable energy production, highlighting its role in minimizing landfill usage and lowering greenhouse gas emissions. It further examines the obstacles and barriers to biogas production from fish waste, including technological, regulatory, and economic factors. By systematically and transparently compiling the literature, we aim to establish a clear framework for future research on fish waste as a renewable energy resource in South Africa. This review aims to: (i) evaluate the potential of fish waste for biogas and biomethane production; (ii) identify factors influencing yield, including co-digestion and pre-treatment; and (iii) assess environmental and economic implications to guide sustainable energy strategies.

2. METHODOLOGY

This systematic review comprehensively examines literature related to various aspects of biogas. Relevant studies were identified, and the data was systematically extracted and synthesized following the PRISMA checklist.

2.1. Criteria for Eligibility and Screening

The chosen literature includes randomized controlled trials, cohort studies, case-control analyses, various forms of observational research, and systematic reviews, encompassing scoping and umbrella reviews centred on fish waste in South Africa, specifically marine and aquaculture waste. Interventions that pertain to Biogas production processes utilizing fish waste were incorporated, such as size reduction, enzymatic hydrolysis, and co-digestion with additional substrates. The primary outcome measured was the yield of biogas, specifically the volume produced per ton of fish waste, alongside biomethane yield, which refers to the methane content within the biogas. Secondary outcomes included the environmental impact, specifically the decrease in greenhouse gas emissions and the diversion of waste from landfills. Considerations of economic feasibility, such as cost-benefit analysis and the potential for energy cost savings, alongside social and regulatory barriers, including challenges in policy implementation and public acceptance. Strategies Interventions that qualify include biogas production processes that utilize fish waste, such as size reduction, enzymatic hydrolysis, and co-digestion with other substrates. The analysis compares traditional disposal methods for organic waste, including agricultural and municipal solid waste, and biogas production's environmental and economic impacts. The search used databases like Embase via Elsevier, Web of Science, Scopus, and Google Scholar, covering September 2, 2024. The study included studies published in English and used a database with similar articles, reference lists, and backward citation analysis. The search results underwent a systematic screening process, with articles that met eligibility criteria obtained, reviewed, and cited. Studies were included if they investigated biogas or biomethane production from fish waste, reported quantitative yield data, and were published in English. Exclusion criteria included incompatible study design, insufficient methodological detail, irrelevant outcomes, and publication type restrictions. The selection process was meticulously documented, enabling the creation of a PRISMA flow diagram (Fig. 1).

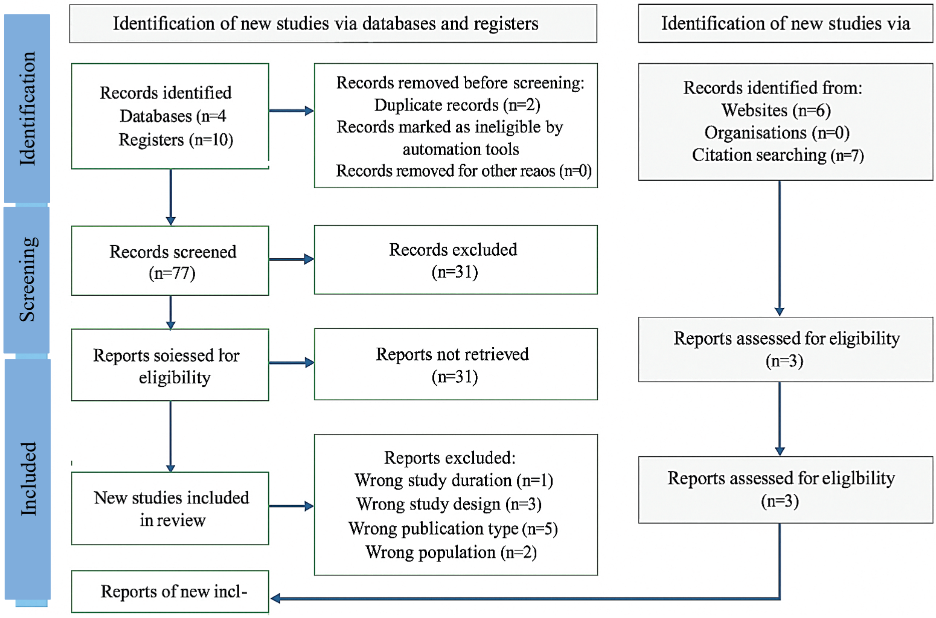

Fig. 1. Prisma flow diagram [12] showing the literature search process that was reviewed.

2.2. Data Extraction

The study analysed various research methods, including randomized controlled trials, cohort studies, case-control studies, observational studies, and systematic reviews. The primary interventions were waste classifications, and the main outcome was biogas or biomethane yield. The environmental impact was secondary, focusing on reducing greenhouse gas emissions and waste diversion. Economic feasibility was assessed, considering cost-benefit analysis and energy cost savings. Challenges related to social dynamics and regulatory frameworks were also considered, including policy implementation and public support. The investigation utilized various approaches and included participant characteristics.

2.3. Methodological Quality

The Risk of Bias was assessed for each study using the ROBINS-I program [13], [14]. The study extracted data on fish waste types, biogas and biomethane yields, pre-treatment methods, co-digestion substrates, retention time, waste reduction, economic feasibility, and outcome measures. The systematic review of studies found that most had moderate methodological quality, with minimal risk of bias in confounding factors, measurement of outcomes, and reporting results. However, some studies showed moderate to serious risk of bias in participant selection and deviations from intended interventions. Some of these issues underscore the need for cautious interpretation, especially in studies with substantial participant selection bias. Despite these concerns, most studies consistently measured and reported outcomes, supporting an overall moderate quality assessment.

3. RESULTS

This presents the study's findings, systematically addressing each research question through both quantitative and qualitative methods, enhancing interpretation and discussion in subsequent sections.

3.1. Study Inclusion and Data Synthesis

Fig. 1 showcases the Prisma flow diagram, which directly interprets the steps undergone in evaluating relevant studies relating to our research question. In the initial identification stage, 77 records were identified from four databases. 16 additional records (six from relevant websites, three from organizational reports, and seven identified through citation searching) were identified. This brought us to a total of potentially relevant records to 93; after removing two duplicate records and 33 records identified as irrelevant by automated tools, 77 unique records proceeded to the initial screening phase. During this phase, each record's title and abstract were reviewed for relevance, resulting in the exclusion of 31 records primarily due to a lack of alignment with the study's inclusion criteria. A total of 46 records were thus retained for the full-text review. Of the 46 records sought for full-text retrieval, 31 could not be retrieved due to journal access restrictions or lack of full-text availability. To enhance transparency, we categorized the 31 studies excluded at this stage, with primary reasons as: incompatible study design (n = 12), insufficient methodological detail (n = 8), irrelevant outcomes (n = 7), and publication type restrictions (n = 4). These categories reflect the application of our predefined eligibility criteria and are now explicitly reported to improve reproducibility and clarity in the review process.

Consequently, 15 records proceeded to the eligibility assessment phase. During this phase, reports were evaluated in detail against the study's eligibility criteria, excluding 11 additional records. Reasons for exclusion included inappropriate study duration (1 record), non-compatible study design (3 records), publication type (3 records), and mismatched study population (2 records). Of the 15 reports that underwent detailed eligibility assessment, four studies were excluded based on specific criteria related to methodological quality, such as lack of randomization or insufficient follow-up data. This left 35 studies that fully met the inclusion criteria and were incorporated into the final review. The included studies represent a diverse array of methodologies and populations that align with the scope of this systematic review. The study selection process was comprehensive and rigorous, as demonstrated in Fig. 1. The data synthesis outlined the relevance of studies to biogas yield, environmental impact and feasibility and co-digestion of fish waste for biogas production (Table 1).

3.2. Characteristics of Included Studies

The qualitative synthesis presented in Fig. 2, Fig. 3 and Table 1 encapsulate all aspects of studies investigating the potential for biogas and biomethane production from fish waste, emphasizing substrates, environmental implications, and economic viability. Table 1 displays biogas yield data derived from the included research. However, the units and metrics supplied by the authors were inconsistent (e.g., m^3/ton, m^3/kg, mL/g VS).

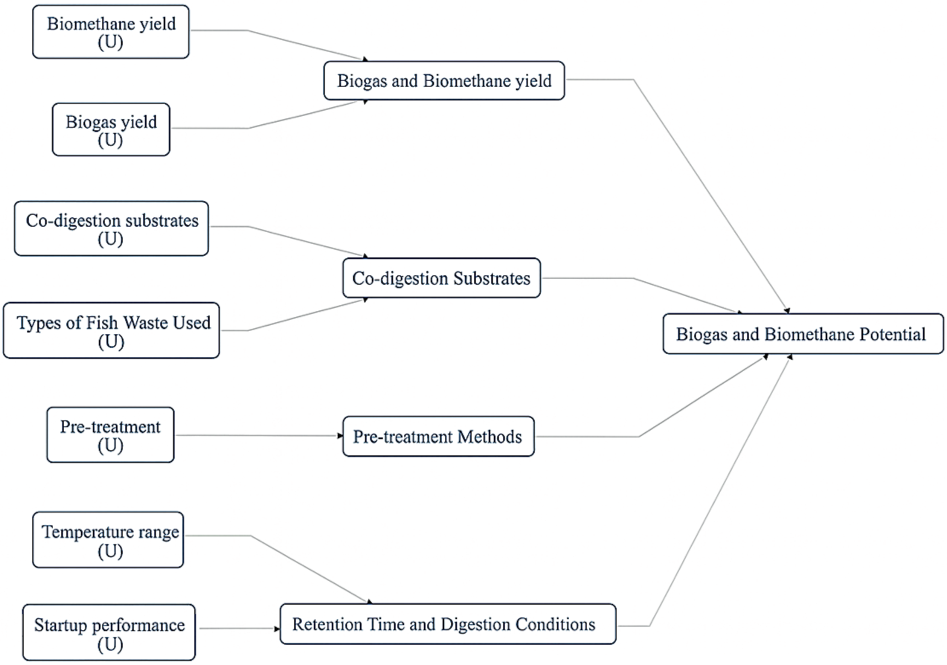

Fig. 2. Meta-Aggregative Flowchart detailing the relation of different parameters influencing biogas and biomethane yield.

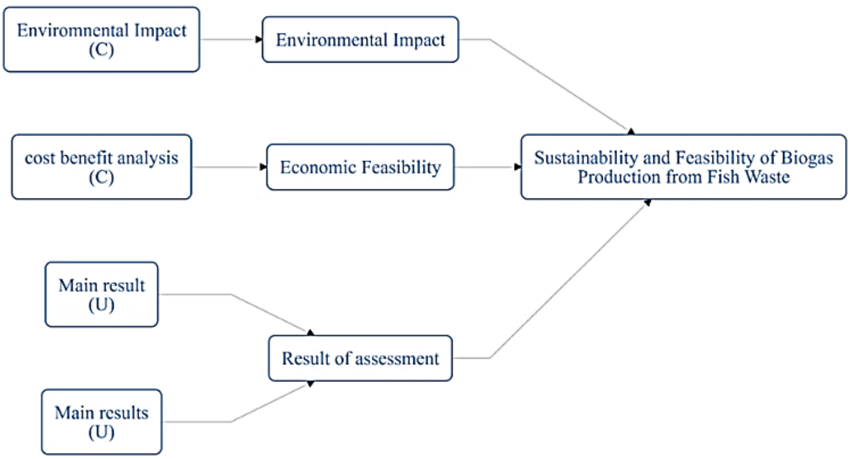

Fig. 3. Meta-Aggregative Flowchart detailing the relation of different parameters influencing the Sustainability and feasibility of biogas production from fish waste.

To enhance comparability, we normalized values by converting reported yields to a uniform metric (m^3 CH_4 per ton of substrate) utilizing available volatile solids (VS) and density data. In instances where conversion was impracticable due to absent parameters, the original units were preserved, and this constraint is acknowledged. Future research should implement standardized reporting metrics, such as m^3 CH_4 per kg VS, to enhance meta-analysis and inter-study interpretation.

TABLE 1. PRIMARY OUTCOMES AND BIOGAS YIELD DATA OBTAINED FROM THE STUDIES ANALYSED FOR THE COMPARATIVE META-ANALYSIS

Co-digestion substrates	**Outcomes measured**	**Biogas Production yield**	**Author**
Food waste and wastewater sludge	The study analysed the methane yield and COD degradation rate of various microbial seeds, using the formula $R1$ = mL/g VS added	The biogas production reached a maximum of 350.5 ± 5.2 mL/g VS, with the highest methane content of 66.1 ± 3.5 %	[15]
Sewage sludge	The study examines biogas and methane production from fish waste and sewage sludge, its content, and kinetic parameters like methane production potential and maximum rate	Biogas yield: 80–140 mL/g VS - Methane content: Exceeding 50 %, with up to 66.44 % methane content	[16]
Swine manure and cow manure	1. Biogas potential of fish waste 2. Methane potential 3. Volatile solids (VS) removal	1. Biogas yield: 757 mL/g VS 2. Methane yield: 554 mL/g VS	[17]
Fish farming sludge from a salmon breeding farm	The study investigates biogas and methane production from fish waste and sewage sludge, its content, and kinetic parameters like methane production potential and maximum rate	The biogas produced methane yields ranging from 223.13 to 370.19 m^3 CH_4/ton and 4.34 to 8.65 m^3 CH_4/ton, with a 63.3 % to 74.6 % methane content	[18]
Fish waste, water hyacinth, inoculum, and blood Retention	The study analysed the total biogas production from various feedstock ratios of water hyacinth and fish waste and the percentage of methane in the biogas	The biogas yield and biomethane content of the fish waste and water hyacinth are 0.56 L and 0.46 L, respectively, with water hyacinth alone having a higher content	[19]
Vegetable market waste (VMW) used with mixed fish waste (MFW) in different ratios	The study demonstrates biogas production from various fish waste samples and vegetable market waste, with precise biogas yield achieved through co-digestion	The biogas yield reached its highest at 1657 mL with a 1:3 MFW to VMW co-digestion ratio, with a maximum specific biogas yield of 0.489 L/g VS	[20]
Cow manure, agricultural waste, and food processing waste	The study assessed biomethane potential in volatile solids, revealing yields ranging from 0.2 to 0.9 m. CH_4 per kg VS. Ammonia release was found to stabilize anaerobic digestion and hinder methane production	Biomethane production varies with the introduction of volatile solids, with methane concentration in biogas typically 55–65 %, indicating energy quality and being influenced by conditions and treatment techniques	[21]
Jerusalem artichoke	The study explores methane production from anaerobic digestion of fish waste, sludge, and Jerusalem artichoke, analysing substrate composition and biogas production, with potential for large-scale biogas generation and bio-fertilizer creation	Biogas yield: 828 ± 15 m^3 CH_4/ton for fish waste, 742 ± 17 m^3 CH_4/ton for fish sludge	[22]

While environmental and economic considerations were noted, their treatment in the reviewed studies was largely descriptive, limiting actionable insights. For instance, although several papers referenced reduced greenhouse gas emissions and potential cost savings, few quantified these benefits or compared them against conventional waste management practices. Similarly, economic feasibility was often discussed without detailed cost–benefit analyses or life-cycle assessments. This gap highlighted in Table 2 underscores the need for future research to incorporate standardized metrics for environmental impact (e.g., carbon footprint, energy balance) and economic performance (e.g., net present value, payback period). Such evaluations would enable policymakers and industry stakeholders to make informed decisions regarding the integration of fish waste into biogas production systems. The included studies span various regions, concentrating on countries with significant fish waste production and biogas energy demand including South Africa, South Korea, China, Brazil, Norway, Iraq, Portugal, etc. Study designs include experimental setups for co-digestion processes conducted in the controlled laboratory [26]–[29], Cross-sectional observational survey, and literature reviews on the utilization of biogas as an energy source [10], [30]–[32]. This diversity in focus and setting reflects the factors influencing biogas production from fish waste. Reported biogas yields were standardized where possible to m^3 CH_4 per ton of substrate. Original units were retained when conversion was not feasible due to missing data (Table 1).

TABLE 2. RECOMMENDED ENVIRONMENTAL AND ECONOMIC INDICATORS

Indicator	Description	Why Important
Carbon Footprint (kg CO_2e)	Total greenhouse gas emissions from process	Measures climate impact
Energy Balance (MJ)	Net energy gained vs energy consumed	Determines process efficiency
Water Use (m^3)	Volume of water required for digestion	Assesses resource sustainability
Net Present Value (NPV)	Economic return over project lifetime	Evaluates long-term profitability
Payback Period (years)	Time to recover initial investment	Indicates financial feasibility
Cost per kWh (USD)	Cost of energy produced compared to alternatives	Supports market competitiveness analysis

Fish waste types varied across studies, with many focusing on processing by-products such as fish guts, scales, heads and processing residues. Additional substrates like cow manure [17], [21], [26], [28], [29] and vegetable market waste [20], sewage sludge [9], [16], [18], [30]–[34], food waste [15], [21], [27], [30], [31], [35], were included to balance the carbon-nitrogen ratio, which is crucial for optimizing anaerobic digestion. Co-digestion substrates were selected based on availability and compatibility with fish waste, aiming to maximize biogas production and methane content [29], [32].

Experimental conditions varied considerably across studies. Temperatures were predominantly set to mesophilic (25–40 °C) [19], [36] or thermophilic [37], [38] (45–60 °C) levels, depending on the type of substrate and desired biogas yield. Retention times ranged from 15 to 60 days, with longer durations generally associated with higher methane yields [17]. Several studies applied pre-treatment methods, including ensiling fish waste with formic acid to reduce contamination and enhance microbial activity [28], thermal pre-treatment [32], [39] (cooking) and mechanical separation (pressing and centrifugation) [32], [39]. Fish waste was crushed, screened, refrigerated, and frozen prior to use [16], [17], enzymatic and thermal processes to enhance the efficiency of substrate degradation [21], [22]. These methods aimed to break down complex proteins in fish waste, thereby improving the biodegradability of the substrate.

Comparative studies frequently observed that co-digestion with additional substrates, particularly cow manure or vegetable waste, agricultural waste, produced significantly higher biogas yields and a richer biomethane yield than fish waste alone [20], [21], [32]. The enhanced performance is likely due to the balanced carbon-nitrogen ratio and improved microbial diversity facilitated by co-digestion [26]. In several studies, methane yields increased by 20–40 % when fish waste was co-digested, indicating the potential benefits of combining substrates for biogas production.

The primary outcome across studies was biogas yield, typically measured in litres per gram of volatile solids (L/g VS). Methane content was also a key metric, with most studies reporting methane percentages between 55 % and 65 % [16]–[18], [21], [36], [39], [40] of total biogas output. Secondary outcomes included reductions in greenhouse gas emissions when biogas was used as an alternative to fossil fuels [11], [16], [33], and organic matter degradation rates, which ranged from 50 % to 80 %. Studies assessed environmental impact using greenhouse gas emissions metrics and life cycle assessments [21], [40]. Results indicated an impressive decrease in emissions observed when fish waste was redirected from conventional disposal techniques to biogas generation.

Several studies conducted lifecycle assessments to evaluate the environmental impact of biogas production from fish waste [41]. Results indicated significant reductions in greenhouse gas emissions when fish waste was diverted from traditional disposal methods to biogas production [6], [25], [33], [37], [42]. Additionally, methane production from fish waste provided a renewable energy source that helped offset fossil fuel consumption, further reducing the environmental footprint.

Economic assessments across studies revealed a favourable cost-benefit ratio for biogas production from fish waste, particularly when co-digested with low-cost substrates [10]. Recommendations for subsidies or carbon credits were common, highlighting their role in making biogas production from fish waste financially viable. Common limitations noted in the studies included variability in fish waste composition, which affected consistency in biogas yields. Biogas production from fish waste, mainly through co-digestion, presents a viable waste management strategy with potential economic and environmental benefits. The success of this approach depends on optimizing substrate combinations and pre-treatment processes and overcoming regulatory and logistical challenges [43]. Future studies could focus on scaling pilot projects, refining economic models, and developing policies to support widespread fish waste biogas production adoption. The analysis of biogas production from fish waste highlights quantitative and qualitative findings regarding the effectiveness and sustainability of this approach.

The quantitative synthesis, depicted in the forest plot (Fig. 4), showed the differences in biogas yield between co-digestion and the digestion of fish waste alone through various studies. The pooled mean difference was 0.23 with a 95 % confidence interval ranging from –0.04 to 0.51, indicating that the interval includes zero and thus no statistically significant difference in biogas yield between co-digestion and fish waste alone. Additionally, the forest plot revealed high heterogeneity among the studies ($I^2 = 100$ %), signalling significant variability in effect sizes across studies, likely stemming from differences in study design, substrates used, and digestion conditions.

It is important to note that the forest plot analysis (Fig. 4) revealed an I^2 value of 100 %, indicating extreme heterogeneity among the included studies. This level of variability suggests that the pooled mean difference should be interpreted with caution, as the assumption of a common effect size is not supported. The heterogeneity likely arises from differences in substrate composition, pre-treatment methods, retention times, and digestion conditions across studies. Due to inconsistent reporting of these moderators, subgroup or sensitivity analyses were not feasible within this review. Consequently, the forest plot is presented primarily to illustrate variability rather than to imply a definitive pooled effect. Future research should prioritize standardized methodologies and explore subgroup analyses (e.g., co-digestion versus mono-digestion, mesophilic versus thermophilic conditions) to reduce heterogeneity and improve comparability.

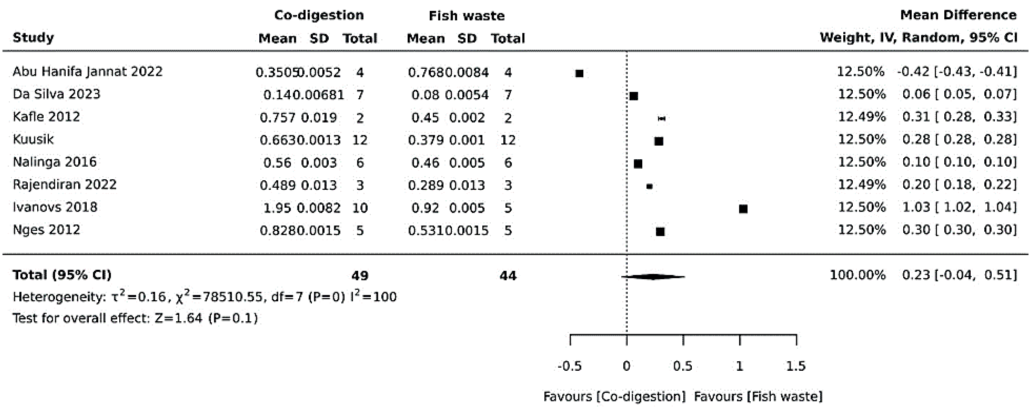

Fig. 4. Findings from the Forest Plot analysis regarding biogas generation focus on mean differences based on the variances observed in the selected studies involving anaerobic digestion.

4. Discussion

The findings align with existing research on biogas production from organic waste and co-digestion processes, which are well-documented as effective methods for converting waste into renewable energy. Past studies have consistently shown that anaerobic digestion is a versatile process adaptable to various organic waste types, with fish waste being a relatively new but promising feedstock. Previous studies in South Africa have primarily focused on agricultural residues and manure as primary feedstocks [9], [11], [30], [33], [44]. The findings of this review reinforce that fish waste offers comparable energy potential, suggesting that fish waste could be integrated into existing biogas systems to diversify feedstock sources. Multiple studies from [5], [6], [35], [45] demonstrated that fish waste is a viable feedstock for biogas production. These studies showed that fish waste has significant energy potential when processed anaerobically, offering an alternative to conventional waste disposal and supporting renewable energy initiatives. Several studies highlighted the benefits of co-digestion, combining fish waste with other organic materials (such as manure, crop residues, or municipal solid waste) to improve biogas yields. For example, studies from [20] reported increased methane production when fish waste was digested with plant-based materials, likely due to improved nutrient balance.

Several studies, such as [46], emphasized the role of factors like feedstock composition, temperature, and pH in optimizing biogas production. Studies investigating the impact of different Fish-to-Microorganism (F/M) ratios showed that adjusting these parameters may improve the efficiency and stability of anaerobic digestion processes. Several investigations examined the decrease in greenhouse gas emissions linked to biogas production derived from fish waste, such as [16]. These studies highlight biogas as a sustainable solution that can help mitigate methane emissions from traditional fish waste disposal practices, contributing to climate change mitigation efforts. Like other research on biogas production, these studies confirmed that co-digestion can improve biogas yields by balancing the nutrient profile, consistent with the literature on agricultural and food waste digestion. By combining fish waste with plant-based or other animal-derived materials, these systems achieve higher methane production, which has also been observed in other co-digestion studies. This review's findings also support the broader environmental narrative that biogas production from organic waste can contribute to reduced greenhouse gas emissions and support circular economy models by turning waste into energy.

The qualitative insights provide a broader context, underscoring the environmental and economic factors contributing to the sustainability of fish waste digestion for biogas production (Fig. 3). The concept map suggests that sustainability assessments should consider biogas yield and weigh the ecological footprint and cost-effectiveness of fish waste digestion. Furthermore, qualitative analysis indicates that factors such as substrate types, pre-treatment methods, retention times, and digestion temperatures influence biogas and biomethane yields, which could explain some of the variability observed in the meta-analysis (Fig. 2). Fig. 2 and Fig. 3 provide schematic concept maps summarizing factors influencing biogas yield and sustainability; however, these visualizations are primarily descriptive and do not offer deeper analytical insights. Future iterations should integrate quantitative relationships or causal pathways to enhance interpretive value. Similarly, the forest plot (Fig. 4) was initially presented without sufficient critical interpretation. Given the extreme heterogeneity (I^2 = 100 %), the pooled mean difference cannot be considered robust. The forest plot serves to illustrate variability rather than to imply a definitive pooled effect and emphasized the need for subgroup analyses and standardized methodologies in future research.

Studies that optimized these conditions often reported better outcomes, but the effectiveness of co-digestion remains inconclusive in this synthesis. These findings align with existing literature, which suggests that co-digestion can enhance biogas yield due to improved nutrient balance and microbial diversity. However, this analysis shows that such improvements are not universally significant, especially when fish waste is co-digested with other substrates. Prior research emphasizes that the compatibility of co-digestion substrates and specific digestion conditions are essential for maximizing yield. Still, such optimization was not uniformly achieved across the studies included in this meta-analysis. While most studies reported improved biogas yields through co-digestion of fish waste with other substrates, this effect was not universal. For example, several investigations demonstrated methane yield increases of 20–40 % when co-digestion was applied, likely due to improved carbon–nitrogen balance and microbial diversity. Conversely, other studies found no statistically significant difference compared to mono-digestion, even under optimized conditions. These contradictions may stem from variations in substrate compatibility, pre-treatment methods, and operational parameters such as temperature and retention time. This inconsistency underscores the need for standardized experimental designs and comparative analyses to determine when co-digestion offers a clear advantage.

In this review, limitations were observed in the design of included studies and in the systematic review itself. Methodological differences across studies, including varying digestion conditions, retention times, and substrate types, contribute to the high heterogeneity observed, complicating the interpretation of a single pooled effect. Additionally, many studies had small sample sizes, limiting the generalizability of the findings, and some lacked detailed reporting on pre-treatment and co-digestion specifics, potentially impacting the accuracy of the synthesized results. The systematic review's scope is also restricted by its qualitative approach to environmental and economic feasibility, as these aspects were not quantitatively assessed, leaving a gap in the sustainability evaluation of fish waste digestion. We consider the limitations where some studies demonstrated moderate to serious risks of bias in domains such as participant selection and deviations from intended interventions, which could impact the validity and generalizability of the results. For example, several studies relied on convenience samples or specific fish waste sources that may not represent the broader waste composition, limiting external validity. There was considerable variability in the operational parameters (e.g., temperature, pH, F/M ratio) across studies, which complicates crosscomparison and synthesis of results. This lack of standardization means that the findings on optimal conditions for biogas production are not universally applicable and need further validation. Many studies focused on specific regions, such as South Africa, Korea, China, Egypt, Norway and Brazil, where fish waste may differ in composition and availability compared to other parts of the world. As such, these findings may not be directly transferable to other regions without considering local waste composition and regulatory environments. Due to inconsistent reporting across studies, some critical information (e.g., missing data, selection criteria for feedstocks) were either unclear or unavailable. This limited the ability to perform a more granular analysis of specific variables affecting biogas production. The included studies varied widely regarding study design, methodological rigor, and outcome measures. This heterogeneity limited the review's ability to synthesize results quantitatively, as pooling data for meta-analysis was not feasible. Given the emphasis on studies reporting positive results on biogas production potential, there may be a publication bias where studies with null or negative findings were not published or not included in this review. This can skew the perceived effectiveness of fish waste as a biogas feedstock. The review's failure to sufficiently address the variation and comprehensively evaluate sustainability outcomes limits its effectiveness. The methodological quality and variety of existing studies limit the current evidence, making the additional benefits of co-digestion unclear.

However, fish waste demonstrates the potential for biogas production. Further investigation requires the implementation of defined techniques and thorough reporting. Integrating sustainability indicators would provide a more exhaustive comprehension of the possible benefits and drawbacks of fish waste digestion, hence promoting the widespread implementation of this method as a feasible and sustainable energy alternative. The studies reviewed collectively provide moderate-quality evidence supporting the use of fish waste as a viable feedstock for biogas production, especially when co-digested with other organic materials. However, limitations in study methodologies, geographic focus, and process variability necessitate caution in generalizing these findings. Future research should aim to standardize study protocols, explore fish waste co-digestion in diverse geographic settings, and address methodological weaknesses to strengthen the evidence base for this promising waste-to-energy approach. While fish waste and co-digestion show promise for biogas production, the meta-analysis reveals significant heterogeneity that underscores the need for standardized methodologies in future research. Such standardization could enhance the comparability of results and provide a more robust understanding of biogas production's efficacy and sustainability from fish waste sources.

5. CONCLUSION

This review provides new insights into the potential of fish waste as a substrate for biogas and biomethane production in South Africa. The synthesis reveals that while fish waste is a viable feedstock, the benefits of co-digestion are inconsistent, with improvements in methane yield observed in some studies but not universally confirmed. Extreme heterogeneity (I^2 = 100 %) across studies underscores the need for standardized methodologies and reporting units (e.g., m^3 CH_4/kg VS). Furthermore, the review identifies critical gaps in environmental and economic assessments, which remain largely descriptive. These findings suggest that future research should prioritize controlled co-digestion trials, integrate sustainability indicators such as carbon footprint and net present value, and adopt uniform protocols to enable robust meta-analysis. For researchers, these results highlight the importance of methodological rigor and comprehensive impact evaluation, while policymakers should consider incentivizing waste-to-energy initiatives and supporting standardization to advance South Africa's Just Energy Transition.

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