A Review: Cleaner Production Strategy for Fish Wastewater: Recovery of Resources and Sustainable Treatment Strategies

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Abstract

Applying one of the environmental techniques is crucial to reducing ecosystem pollution, such as cleaner production (CP), which helps mitigate marine water pollution by recovering useful components from wastewater, thereby enhancing environmental performance. This review paper is based on secondary data and presents various cleaner production strategies and their potential for enhancement. By focusing on effluent reduction, using the valuable by-products, developing a treatment approach, and reducing energy usage. The paper shows that all studies found that a cleaner production approach improves the effectiveness of standards for wastewater recovery, including fats and solids, thereby strengthening the global fisheries sector by applying cleaner production processes. A cleaner production process relies on a recovery method and focuses on metrics to prevent and preserve marine water, achieving eco-friendliness and effectiveness in the fisheries industry.

Keywords: Cleaner production, Wastewater, Fishery, Sustainable

1. Introduction

Cleaner production is an environmental management technique that combines and implements measures to reduce the environmental effects of generating processes and outputs throughout their life cycles. It is intended to minimize waste at the source, thereby reducing the pollution severity and enabling the reuse of manufactured waste products (Jespersen, Christiansen and Hummelmose, 2000).

Also, cleaner production (CP) is an environmental approach highly adopted in the Ecuadorian artisanal fishing field to reduce marine pollution and improve serviceability. This method focuses on preventing contamination at its source by reducing or eliminating emissions, toxic raw materials, waste, and dumping, rather than treating wastewater at the end of the pipe (Enrique *et al.*, 2017).

It includes the consistent implementation of comprehensive preventive environmental measures across key processes and services to enhance eco-efficiency and reduce health and environmental danger. The main purpose is to avoid excessive waste production, which results in economic losses and pollution (Enrique *et al.*, 2017; Science, 2021).

By following CP techniques, the goal is to recover valuable components from wastewater, improve environmental performance, expand manufacturing capacity, and enhance the organization's image among stakeholders (Sarkar *et al.*, 2006; Enrique *et al.*, 2017). This approach ensures the effective use of substances, inputs, and organic resources, which often need technological retransformation and process redesign to reduce waste and enable retreatment (Enrique *et al.*, 2017).

The implementation of cleaner production techniques is the initial and essential step in controlling wastewater within enterprises, promoting the effective use of raw materials, energy, and water, and thus minimizing the need for extensive final treatment and production costs (Singh Asiwal *et al.*, 2016; Enrique *et al.*, 2017).Cleaner Production (CP) methods in the Danish fishery handling sector have primarily focused on reducing fishery wastewater, with essentially a focus on finding solutions and process improvements. These enterprises involve reuse, recycling, and good housekeeping practices, as well as technological changes, to reduce water intake and effluent emissions.

Particular examples of cleaner production solutions for wastewater include the dry move of fish waste and fish, which reduce water utilization and the natural content in effluent. Dry elimination of skin and guts, reached through modified machines, additionally minimizes organic matter in wastewater flows. Moreover, the manufacturer has implemented measures, such as separating fish oil from waste product streams via spinning, thereby reducing contamination and creating beneficial by-products (Thrane, Nielsen and Christensen, 2009; Dhanke, Wagh and Patil, 2019).

Generally, these endeavors have led to significant reductions in Chemical Oxygen Demand (COD) emissions and water consumption, with metrics of 3 and 5, respectively, across a 15-year period, illustrating the efficiency of these CP methods in controlling fishery wastewater (Lara-isassi, 1995; Sarkar *et al.*, 2006; Thrane, Nielsen and Christensen, 2009; Varadarajan, Meganathan and Manohar, 2021).

Cleaner production methods for fishery wastewater are essential for reducing environmental effects and improving sustainability within the fishing enterprise. These techniques focus on reducing waste at the source, optimizing resource use, and restoring valuable by-products, rather than relying only on end-of-pipe purification. Key approaches involve process optimization, such as enhancing treatment and processing methods to minimize water use and natural load in effluent, and implementing advanced separation and filtration technologies to recover pills, proteins, and solids from wastewater streams (Afonso and Bórquez, 2003; Science, 2021). Additionally, valorizing fishery by-products, such as fish bones, trimmings, and heads, into high-value outputs, such as fish oil, collagen, fishmeal, or even biofuels, aligns with circular economy principles by converting waste into resources. This not only decreases the toxicity and volume of discharged wastewater but also generates new income flows and boosts the overall economic efficiency of fishery production, contributing to a more environmentally and sustainably responsible seafood area (Fletcher *et al.*, 2015; Science, 2021; Pipaliya *et al.*, 2026).

Although one written document was provided mainly explains cleaner production in the situation of hospital effluent, the principles are applicable worldwide. In the fishery sector, CP would include identifying inefficiencies in handling, such as excessive water use during cleaning, insufficient treatment of fish waste, or inappropriate effluent treatment before dumping. By implementing procedures such as optimizing water use, recovering valuable by-products from fish waste (e.g., for animal feed or fertilizer), improving wastewater treatment to minimize pollution, and applying developed effluent treatment methods that enable water reprocessing, the environmental impact of fishery operations can be essentially decreased. This technique not only advances environmental sustainability by minimizing waste and contamination but also provides economic benefits by reducing generation costs and increasing operability, as it does in other sectors, thereby improving effluent-handling performance (Jespersen, Christiansen and Hummelmose, 2000).

While the core fundamentals of CP are classified into three groups, the first is waste reduction at the source, the main purpose of which is to reduce waste creation rather than processing it after it is generated. This includes processing optimization, raw substance replacement, and good household expertise. Secondly, it involves a comprehensive environmental approach: cleaner production, an integrated technique applicable to the entire production process, from raw material extraction to final product dumping. Then, resource effectiveness, which ensured the effective use of resources, involved energy, raw materials, and water, resulting in lower maintenance costs and higher profits (Jespersen, Christiansen and Hummelmose, 2000).

On the other hand, the application of wastewater in the fishery involves processing improvements, including redesigning the fish processing lines and analyzing to minimize water use, reduce overflows, and enhance the recovery of solid waste products. Also, involves by-product recovery rather than dumping in fishery effluent, exploring possibilities to convert it into useful products, such as fish oil, compost, or fishmeal, thus minimizing the natural load in wastewater (Aspé, Martí and Roeckel, 1997).

Also, water recycling and reuse are required to treat the effluent and use it for many purposes, except for potable uses, such as facility or aquaculture uses, and cleaning, which reduces freshwater requirements and wastewater dumping. Additionally, technology implementation to apply biological medication, advanced filtration, or modern methods to ensure that any discharged water exceeds or meets ecosystem quality norms (Veiga, Méndez and Lema, 1994).

In brief, applying a cleaning production approach to fishery wastewater involves a comprehensive strategy to reduce waste, recover value, and improve resource efficiency. While the aim is more traditional treatment on the end-pipe, merging environmental considerations into all production processes. That results in economic and environmental benefits (Jespersen, Christiansen and Hummelmose, 2000).

2. Materials and Methods

Since the work is based on secondary data, the data were extracted from previous studies and web-based information. Case studies and data analysis have been used in literature papers to obtain more details on the application of a cleaner production strategy for fish wastewater. The study aims to identify resource recovery and sustainability, and to apply treatment methods.

3. Characteristics of Fishery Effluents

Fishery wastewater exhibits various characteristics that affect its management and transformation into useful outputs. It is worth noting that the main components of fishery wastewater are fish heads, frames, fins, and guts, which account for the largest share of seafood litter from fish processing. Diverse shellfish waste, which fish litter does not have a critical amount of chitin, is mainly in shell remains (Tg and Pv, 2018).

Also, it is important to note that fish waste is rich in assimilable protein. Where high protein concentration releases hydrogen sulfide and ammonia during the composting. That leads to a loss of nitrogen through the release of ammonia and other nitrogen compounds, which is crucial because nitrogen is a key element contributed by protein. This makes the composting process less efficient and can prevent it from running properly (Ziani *et al.*, 2007; Tg and Pv, 2018).

Another feature of fishery effluent is salinity: seafood waste generally has a high salinity level; shellfish waste contains high levels of chitin from shells, which should be taken into consideration in the composting process.Besides, the rapid release of ammonia from calcium and the degradation of protein in fish bones help raise the pH of the compost mixture to an alkaline level. In turn, the utility of a bulking factor with acidic properties can help lower the pH (Veiga, Méndez and Lema, 1994; Ching and Redzwan, 2017). On the other hand, in usual seafood waste, the high moisture content affects composting processes and the selection of bulking metrics (Borg-Stoveland *et al.*, 2024).

In conclusion, fishery wastewater is characterized by high protein and natural content, leading to the release of substantial amounts of hydrogen sulfide and ammonia during decomposition; high salinity; a low carbon-to-nitrogen ratio; and high moisture content. The properties underlined the demand for particular management methods, such as operated composting with bulking factors to turn them into valuable products, such as natural fertilizers (Tg and Pv, 2018).

4. Cleaner Production Concept in the Fishery Industry

The Cleaner Production approach in the fish processing enterprise is a consistent, comprehensive, preventive environmental strategy that extends across processes, products, and services to improve overall effectiveness and minimize risks to both the environment and human health. Even this method differs from the conventional pollution-monitoring approach by adopting a proactive, anticipatory, and preventive philosophy, targeting to prevent contamination and waste at the source of supply (Jespersen, Christiansen and Hummelmose, 2000).

This method varies from conventional pollution monitoring techniques by following a proactive, anticipatory, and preventive philosophy, targeting to prevent contamination and waste at the source of supply. The fishery enterprises themselves face critical environmental challenges, including energy consumption, high water use, and wastewater with high levels of natural content and solid waste (Jespersen, Christiansen and Hummelmose, 2000; Sharma *et al.*, 2025).

For instance, fish filleting may require 5-11 m^3 of water per tonne of fish input, but preserving consumes about 15 m^3 per tonne, and fish meal and oil generation demand almost 0.5 m^3 of fresh water and 20 m^3 of seawater per tonne. It is remarkable that energy usage is also significant, with filleting absorbing 65-87 kWh, fish meal/oil generation 32 kWh per tonne of fish intake, canning 150-190 kWh, and, in addition, 32 liters of fuel oil (Jespersen, Christiansen and Hummelmose, 2000; Pipaliya *et al.*, 2026).

The crucial environmental matter also involves high water consumption for cleaning, thawing, and transport, substantial energy use for drying, cooking, and refrigeration, and the discharge of wastewater containing high levels of organic substances, protein, suspended solids, and oils from different processing phases. Besides, CP potential focuses on minimizing resource use, improving yields, and lowering wastewater loads.

The work noted that this process includes methods such as enhanced process optimization, housekeeping, new approaches, raw material substitution, and product modernization, with many options being low- or no-cost and offering quick paybacks (Jespersen, Christiansen and Hummelmose, 2000).

As shown, the hake filleting industry minimizes water use for ice removal by 80%, saving 120 m^3 per day with a return of less than 1 week. A different case study demonstrated that a herring filleting manufacturer decreased water usage for cleaning by 75% using a specialty system. CP implementation also helps manage by-products, such as transforming fishing waste into tradable products like surimi, fish meal, or silage, thereby generating additional revenue and minimizing landfill costs (Jespersen, Christiansen and Hummelmose, 2000; L and S, 2021; Tom *et al.*, 2021). Ultimately, Figure 1 illustrates the flow graph for fish meal and fish oil generation, with particularization stages from raw material off-loading through cooking, pressing, drying, and packaging (Jespersen, Christiansen and Hummelmose, 2000; L and S, 2021).

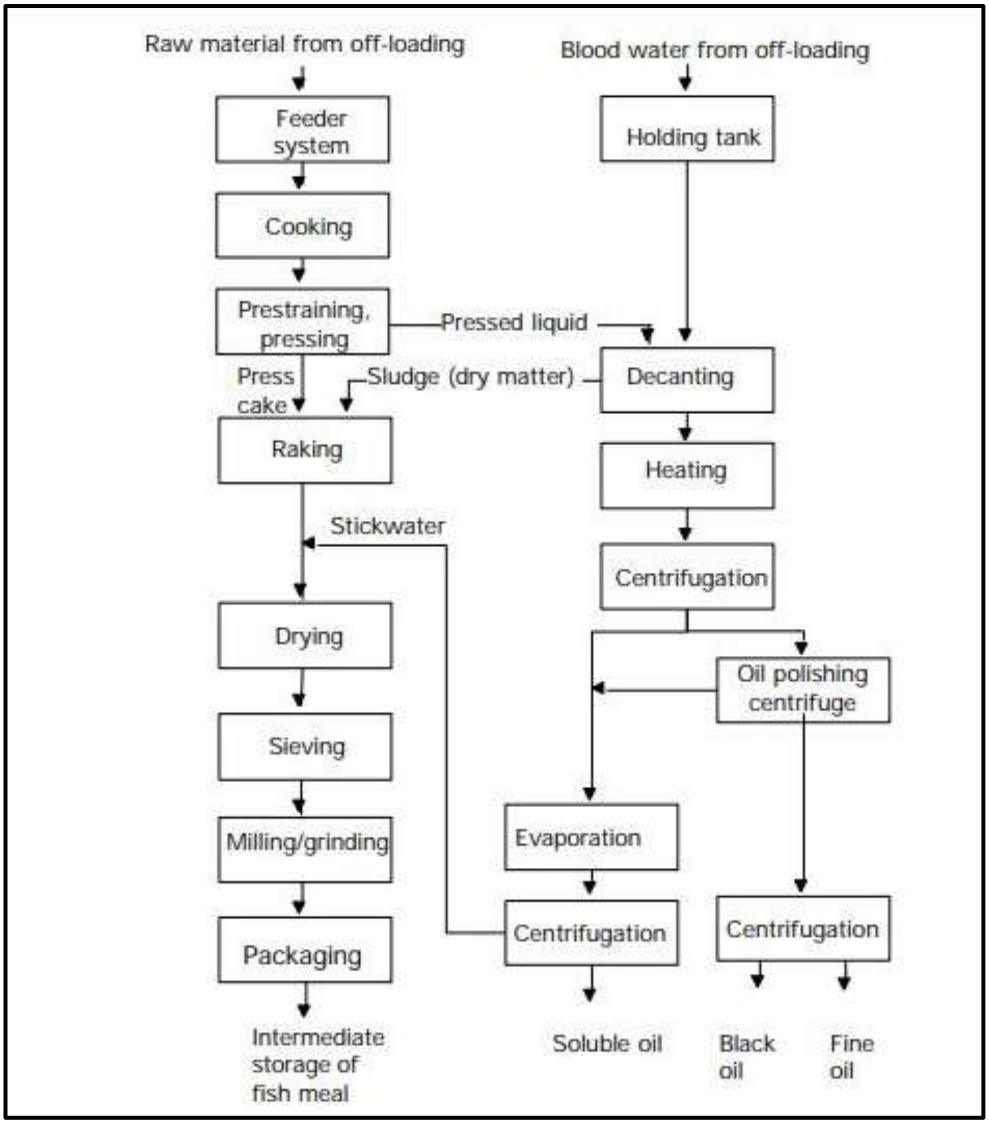

Figure 1: The process of fish oil production and fish meal
Source: (Jespersen, Christiansen and Hummelmose, 2000)

The general aim is to achieve both environmental improvements and economic savings, thereby strengthening competitiveness and improving the environment. These graphical aids help understand complex processes and define specific concepts for CP intervention to improve resource use and reduce waste (Jespersen, Christiansen and Hummelmose, 2000; Bestari and Suharjono, 2015).

5. Resource Recovery from Fishery Effluents

As fish wastewater is a substantial by-product of the fishery manufacturing industry, with useful components that can be recovered and reused, it minimizes environmental impacts and generates economic value. Where the resource is recovered, attempts are frequently centered on oils, nutrients, and protein, with bio-transformation methods having a critical role (A *et al.*, 2022).

4.1 Recovery of Protein and Oils

The authors noted that all waste generated during the fish processing, involving wastewater, is a valuable source of nitrogen compounds, especially protein. Almost 60% of the protein can be recovered while maintaining its inherent qualities. Methods, such as isoelectric dissolving sedimentation, are used to recover myofibrillar protein from various shellfish waste products and finfish (Afonso and Bórquez, 2003; A *et al.*, 2022).

This approach includes solubilization, homogenization at an exceptional pH, isoelectric pH precipitation (pH 5.2 to 6), removal of impurities, and subsequent centrifugation or membrane filtration to isolate the protein. Also, collagen, proteins, bioactive peptides, gelatin, and protein hydrolysates are among the nitrogen compounds that can be derived from shellfish and finfish processing waste (Kaur *et al.*, 2010; Colic *et al.*, 2012; Ye *et al.*, 2020).

In turn, fishery processing waste is a significant source of oil, especially the livers of key finfish species such as cod, tuna, and salmon. The conventional wet mitigation techniques include purification, cooking, and crushing to get the oil, which is otherwise refined through alkali deodorization, antioxidant stabilization, and purification. For example, the guts of fish may contain an important quantity of fatty, about 19-21% of total fatty. Even squalamine, PUFA-rich oil, squalene, B-carotene, astaxanthin, and carotenoids are particular lipid parts that can be recovered from shellfish waste and finfish. Figure 2 presents isoelectric dissolving sedimentation for protein recovery from fish waste (Gómez-Sanabria *et al.*, 2020; Tom *et al.*, 2021; A *et al.*, 2022; Borg-Stoveland *et al.*, 2024).

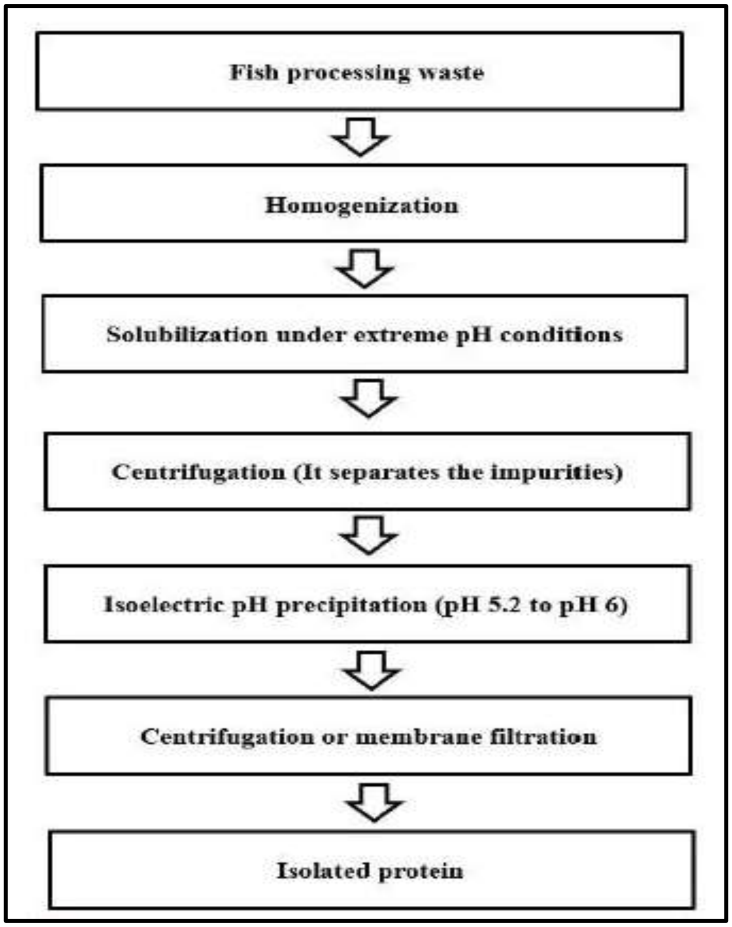

Figure 2: Isoelectric dissolving sedimentation for protein recovery from fish waste
Source: (A *et al.*, 2022)

4.2 Biogas Production

While the provided text does not explicitly address fishery effluents, it notes that wastewater from seafood processing can be a prospective feedstok for eco-friendly biodiesel and biogas generation. The work discusses the potential for biogas generation from these waste flows (Picos-Benítez *et al.*, 2019; Gómez-Sanabria *et al.*, 2020).

4.3 The Recovery of Nutrient

4.3.1 The general recovery of the nutrient

Fishery processing manufacturing waste leads to nutrient loss and causes the main environmental dangers. To handle this issue, the paper suggested subjecting the waste to minor processing and valorization. Biological procedures, such as bioconversion approaches, are cost-effective, safe, and environmentally beneficial for recovering essential components from bycatch, manufacturing wastewater, and throwback without losing their natural bioactivities (Abinandan and Shanthakumar, 2015; Gómez-Sanabria *et al.*, 2020; A *et al.*, 2022; Sharma *et al.*, 2025).

As shown in the papers, biological treatment can convert nutrients into single-cell proteins that can be used for biodiesel generation and as necessary ingredients (Abinandan and Shanthakumar, 2015; Gómez-Sanabria *et al.*, 2020; A *et al.*, 2022; Sharma *et al.*, 2025).

4.3.2 The specific nutrients

Different studies indicated that fish litter contains essential nutrients, including moisture, protein, ash, fat, and other minerals, making it useful for additional treatment. Which typical composition of ash, protein, and fat in fish processing waste was noted as 57.92% ± 5.26%, 19.10% ± 6.06%, and 21.79% ± 3.52%, respectively (Velmurugan and Srithar, 2011; Jana, Mandal and Jayasankar, 2018; Gómez-Sanabria *et al.*, 2020; Borg-Stoveland *et al.*, 2024).

Fundamental minerals such as calcium carbonate, calcium, fish hydroxyapatite, phosphopeptides, shellfish calcium acetate, and calcium lactate can be restored. Additionally, minerals are especially plentiful in fish frames, with bone containing almost 70% of them, which can be used as calcium supplements and in biomedical usage such as bone implants (Jesus *et al.*, 2015; García, 2016; Tom *et al.*, 2021).

To conclude, resource restoration from fishery wastewater is a multifaceted method that leverages biotransformation and other methods to obtain beneficial minerals, proteins, and oils while enabling biofuel generation. This not only reduces environmental contamination but also converts waste into economically valuable outputs (A *et al.*, 2022).

6. Sustainable Treatment Technology

One study examined fish processing in Indonesia, illustrating sustainable effluent management that included a range of treatment approaches to reduce greenhouse gas emissions and water contamination. The paper explained various methods involving biological and physical treatment, as well as more developed approaches. For example, the business-as-usual (BAU) plan basically depends on unprocessed effluent (Gärde, 2011; Gómez-Sanabria *et al.*, 2020; A *et al.*, 2022).

On the other hand, the national wastewater policy (NWP) includes activated sludge and ventilation lagoons, whereas the climate change policy (CCP) uses a swimbuds approach. Briefly, the studies mentioned that the approaches to enhance COD elimination effectiveness and mitigate greenhouse gas emissions. Also, the productivity of those techniques is impacted by elements such as departmental coordination, implementation potential, and multiple networks (Sarkar *et al.*, 2006; Parvathy *et al.*, 2017; Gómez-Sanabria *et al.*, 2020).

Figure 3, shown below, demonstrates the relationship between greenhouse gas emissions and COD elimination effectiveness across various elimination tactics, underscoring the impacts of different processing techniques on environmental indicators (Gómez-Sanabria *et al.*, 2020)

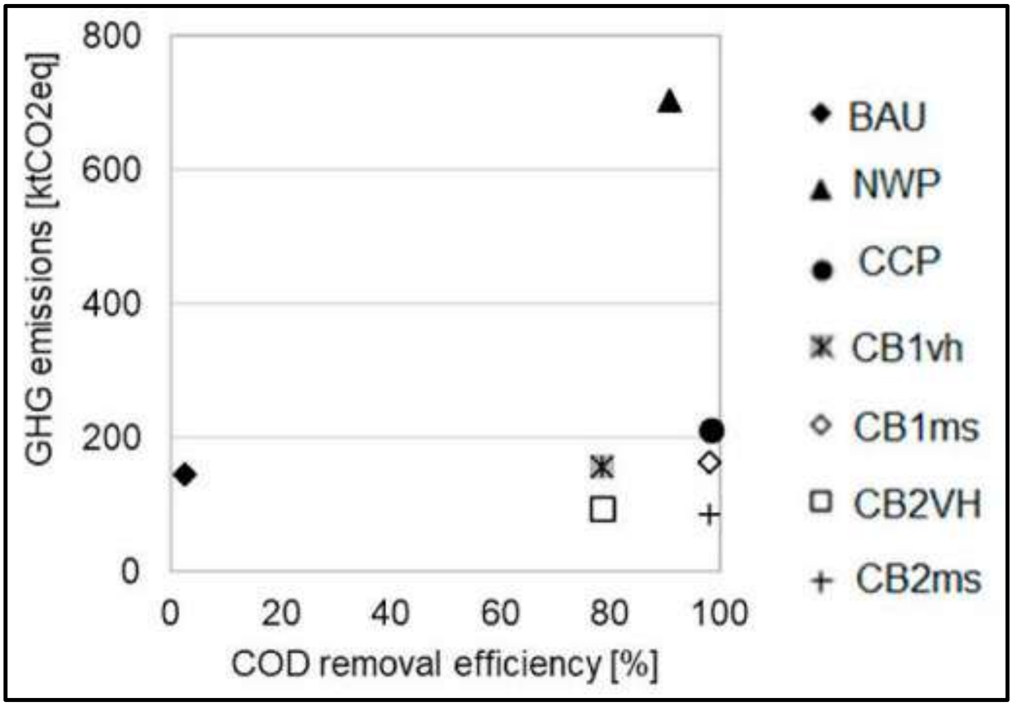

Figure 3: Multifold advantages of the analyzed methods
Source: (Gómez-Sanabria *et al.*, 2020)

Thus, a comprehensive method for effluent processing is essential to achieve Indonesia's ambitious ecosystem goals, which balance contamination mitigation and climate change reduction (Gómez-Sanabria *et al.*, 2020).

7. Integration of Resource Recovery and Wastewater Treatment

A new paper discusses how microalgae are widely acknowledged as a consistent and promising solution for effluent recovery, efficiently integrating resource restoration with the treatment of effluent from diverse sources, including industrial, municipal, and agricultural (Damgaard *et al.*, 2021; Plöhn *et al.*, 2021).

The study assured that this technique is driven by the increasing global demand for fresh water and the rising amount of polluted wastewater. Where microalgae outclass in mitigating contaminants such as phosphorus and nitrogen, the main drivers of eutrophication, and in removing all toxic compounds, such as pharmaceuticals and heavy metals (Afonso and Bórquez, 2003; Plöhn *et al.*, 2021).

Chlorella vulgaris is an example with high elimination effectiveness for total nitrogen (about 89%) and total phosphorus (about 85%). On the contrary, the traditional energy-intensive treatment scheme, photosynthetic microalgae, harnesses sunlight, thereby reducing energy usage and the reclamation process's carbon footprint. The research demonstrated that biomass produced during this process can be valorized into various outputs, involving animal feed, biofuels, and other high-value components, consequently contributing to a rotary bioeconomy (Chlorella, 2020; Carvalho *et al.*, 2021; Ryan *et al.*, 2024).

8. Critical Overview of Trends in The Literature Studies

Available studies have shown a clear discrepancy in the efficiency of cleaner production strategies, especially in the recovery of proteins versus oils. Some research has focused on one aspect, while others have been neglected. This review clarifies points of agreement and disagreement, helping future researchers identify best practices based on available evidence.

9. Conclusion

In conclusion, cleaner production, as an advanced approach, is used to improve industry performance. While conventional methods remain poor and must follow management metrics that may affect productivity, applying CP parameters will meet administrative criteria, cleaner production standards, and structural improvement goals.

Various challenges remain regarding the effects of climate and environmental factors, such as temperature, pH, and light, on microalgal growth and nutrient removal, especially in areas with seasonal variations. And as wastewater is the primary contaminant of marine water, it is essential to move towards cleaner production by adopting eco-friendly techniques to enhance environmental performance, meet legal requirements, and improve process efficiency.

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CONFLICT OF INTERESTS

The authors declare that there is no conflict of interest.

AUTHOR CONTRIBUTIONS

The present work is related to*SDG-6.3 improving water quality by removing pollution*, *SDG-14 Life under water, and SDG-13 Climate action*.All the authors contributed significantly to this manuscript, participated in reviewing/editing and approved the final draft for publication.

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