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# Characterization and Evaluation of Sludge from Seafood Processing Wastewater Treatment: Potential for Composting and Sustainable Reuse

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ABSTRACT

This study characterizes the physicochemical and microbiological properties of sludge from the wastewater treatment system of a seafood processing plant (COIMEX) and evaluates its potential for composting. Post-dewatering sludge samples were analyzed for 26 parameters, including organic matter, nutrients, heavy metals, hazardous compounds, and microbial indicators. Results showed high organic content (TOC: 41.3% dw, VS: 82.1% dw), nitrogen (4.26% dw), and phosphorus (2.72% dw), confirming the sludge's nutrient-rich nature. Heavy metals and toxic organic compounds were mostly below detection limits, while Ba and Zn concentrations remained far below regulatory thresholds. Microbial contamination was moderate (E. coli: 608 MPN/100 mL, coliforms: 7900 MPN/100 mL), with Salmonella absent. However, the fat, oil, and grease (FOG) concentration (8005 mg/kg dw) exceeded the Vietnamese hazardous waste limit, requiring pre-treatment or co-composting strategies. Overall, COIMEX sludge presents strong potential for sustainable reuse as a feedstock for composting, supporting circular economy strategies in Vietnam.

## Introduction

Vietnam has consistently ranked among the world's leading seafood exporters. According to the General Department of Customs, seafood export turnover in 2022 exceeded 10.92 billion USD, marking a 23% increase from 2021 [1]. Vietnam now accounts for about 7% of global seafood trade, placing it among the top three exporters worldwide, after China and Norway [2]. The country's production output reached 9.06 million tons in 2022, reflecting rapid industry expansion [3]. This rapid growth, however, generates large volumes of wastewater and sludge containing high levels of organic matter, nutrients, fats, oils, and pathogenic microorganisms. Without proper management, these by-products may cause secondary pollution to soil, water, and air, while posing public health risks. Therefore, characterizing sludge properties and exploring sustainable management options such as composting is essential to align with Vietnam's circular economy and green development strategies.

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The COIMEX seafood processing plant (capacity 12,000 tons/year) operates a wastewater treatment system of 900 $m^3$/day (Figure 1). The system combines physicochemical, flotation, anaerobic, anoxic, aerobic, and disinfection steps. Sludge is generated at multiple stages and dewatered before temporary storage or external treatment [4]. Given this context, this study aims to evaluate the physicochemical and microbiological characteristics of COIMEX sludge and assess its feasibility for composting and sustainable reuse.

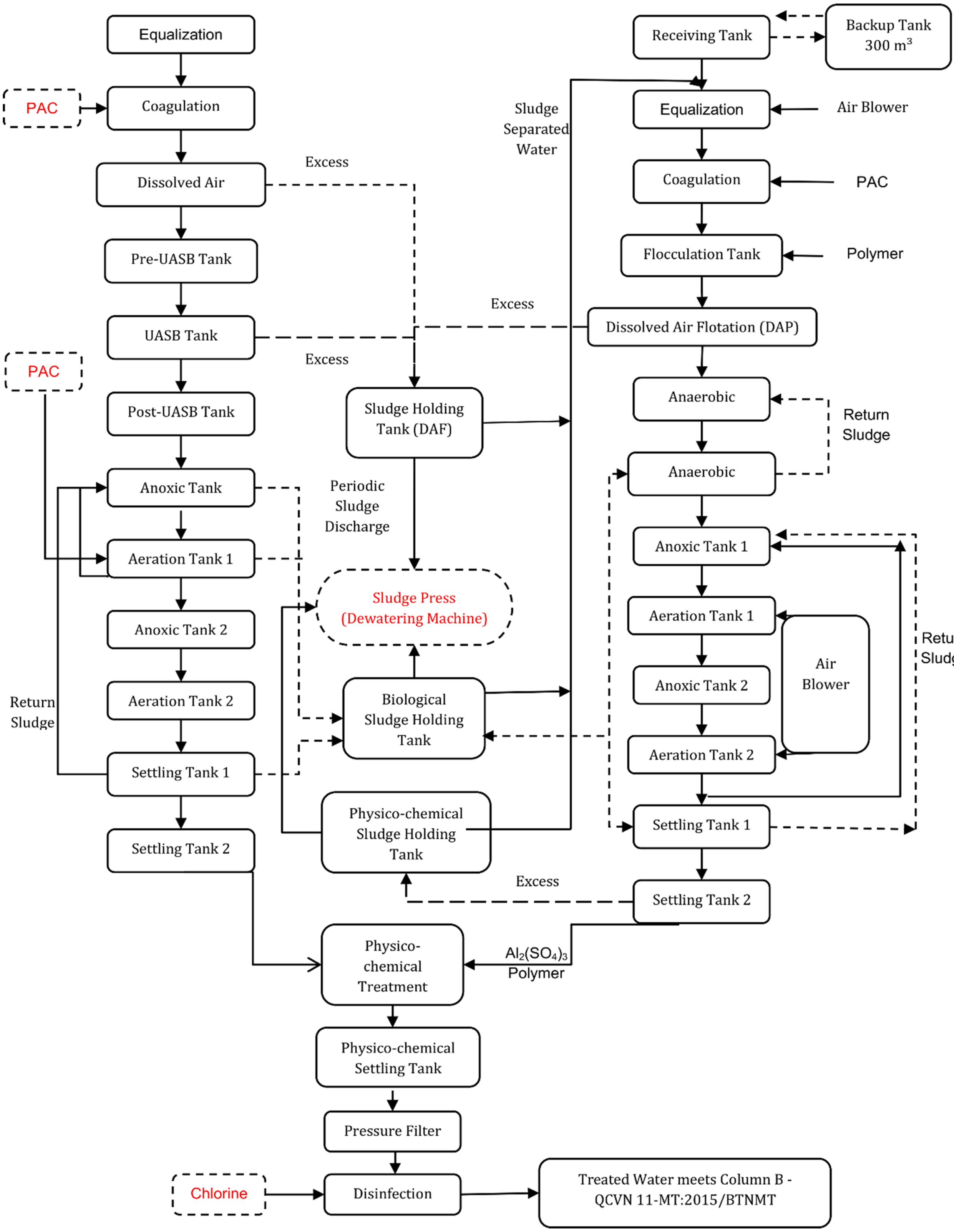


Fig 1: Schematic Diagram of the COIMEX Wastewater Treatment System [4]

## Experimental

Sludge samples were collected from the COIMEX Seafood Processing Plant, under ConDao Seaproducts and Import-Export Joint Stock Company (COIMEX), located at 1738 30/4 Street, Phuoc Thang Ward, Ho Chi Minh City. The sampling point was the post-dewatering sludge at the wastewater treatment system. Sampling procedures followed the Vietnamese standard TCVN 6663-13:2000 (ISO 5667-13:1993) – Guidance on the sampling of sludges from wastewater treatment systems, ensuring representativeness and compositional stability. Sample preservation and handling complied with TCVN 6663-15:2004 (ISO 5667-3:1994).

Sampling was conducted over three consecutive days (March 3–5, 2025). Immediately after collection, the sludge was stored at 4°C in insulated containers, then transported to the laboratory. All physicochemical and microbiological parameters were analyzed at laboratory VIMCERTS 077, using internationally recognized methods (US EPA, SMEWW) and Vietnamese national standards (TCVN) (Table 1).

Microsoft Office Excel was utilized in the study for data management, statistical calculations, and comparison of mean values.

Table 1: Analytical Methods for Sludge Parameters

| Parameter | Analytical Method | Parameter | Analytical Method |
|---|---|---|---|
| pH | US EPA Method 9045D + US EPA Method 9040C | As, Cd | US EPA Method 3050B + US EPA Method 7010 |
| Moisture | TCVN 4048:2011 | Ag, Co | US EPA Method 3051A + US EPA Method 7000B |
| Total solid (TS) | SMEWW 2540B:2012 | Pb | US EPA Method 3050B + US EPA Method 7000B |
| Total Organic Carbon (TOC) | TCVN 8941:2011 | Zn, Ni | US EPA Method 3050B + US EPA Method 7000B |
| Volatile solids (VS) | SMEWW 2540E:2012 | Se, Ba | US EPA Method 3051A + US EPA Method 7010 |
| Electrical conductivity (EC) | TCVN 6650:2000 (ISO 11265:1994) | Hg | US EPA Method 7471B |
| Total Nitrogen (T-N) | TCVN 8557:2010 | Cr(VI) | US EPA Method 3050B + US EPA Method 7196A |
| Total Phosphor (T-P) | TCVN 8563:2010 | $CN^-$ | US EPA Method 9013A + US EPA Method 9010C + US EPA Method 9014 |
| Fat, Oil and Grease (FOG) | US EPA Method 9071B | Phenol | US EPA Method 3540C + US EPA Method 3650B + US EPA Method 8041A |
| E. coli | SMEWW 9221B&F:2017 | Benzen | US EPA Method 5021A + US EPA Method 8260D |
| Coliform | SMEWW 9221B:2017 | Salmonella spp. | TCVN 4829:2005 / ISO 6579:2002 |

## Results and discussion

A comprehensive analysis of 26 parameters was conducted to evaluate the physicochemical and microbiological properties of post-dewatering sludge. Results are summarized in Table 2 and compared with QCVN 50:2013/BTNMT for non-hazardous industrial solid waste.

The sludge showed high moisture (87.7%), consistent with previous reports on seafood sludge [5, 6], which poses challenges for dewatering and storage. Total solids accounted for 12.3%, while volatile solids reached 82% of dry weight (dw), indicating a highly organic and biologically active material suitable for composting but requiring odor and pathogen control. The neutral pH (7.66) falls well within the regulatory limits (2–12.5), confirming that the sludge is not classified as hazardous based on acidity or alkalinity.

Total organic carbon (TOC) was 41.3 ± 0.2% dw, higher than values reported by Vo et al. [7] for Sumiri seafood sludge (33.1%) and typical municipal sludge (15–25%) [8]. Such a high TOC level highlights strong potential as a carbon-rich substrate for composting, especially when co-composted with agricultural residues that balance the C/N ratio, such as straw, sawdust, or rice husks [9]. Volatile solids (82.1 ± 4.1% dw) confirmed that most

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solids are biodegradable, a critical factor for microbial degradation and heat generation during composting [10, 11]. By comparison, municipal sludge generally contains 60–70% volatile solids [8].

Table 2. Analysis Results of 26 Parameters Compared to QCVN 50:2013/BTNMT

| Parameter | Unit | Analysis results | QCVN 50:2013/BTNMT |
|---|---|---|---|
| pH | - | 7.66 ± 0.04 | 2–12.5 |
| Moisture | % | 87.7 ± 0.6 | - |
| Total solid (TS) | % | 12.3 ± 0.07 | - |
| Electrical conductivity (EC) | mS/cm | 2.55 ± 0.02 | |
| Total Organic Carbon (TOC) | % dw | 41.3 ± 0.2 | - |
| Volatile solids (VS) | | 82.1 ± 4.1 | - |
| Total Nitrogen (T-N) | | 4.26 ± 0.08 | - |
| Total Phosphor (T-P) | | 2.72± 0.08 | - |
| Ba | mg.kg$^{-1}$ dw | 66.7 ± 0.3 | 2000 |
| Zn | | 130.9 ± 0.4 | 5000 |
| As (0.09)* | | nd | 40 |
| Ag (1.5)* | | | 100 |
| Cd (0.03)* | | | 10 |
| Pb (5.7)* | | | 300 |
| Co (1.5)* | | | 1.600 |
| Ni (7)* | | | 1.400 |
| Se (0.1)* | | | 20 |
| Hg (0.1)* | | | 4 |
| Cr(VI) (1.8)* | | | 100 |
| Phenol (2)* | | | 20.000 |
| Benzen (0.6)* | | | 10 |
| $CN^-$ (0.3)* | | | 590 |
| Fat, Oil and Grease (FOG) | | 8,005 ± 51 | 1000 |
| E. coli | MPN/100mL | 608 ± 28 | - |
| Coliform | MPN/100mL | 7900 ± 121 | - |
| Salmonella spp. | MPN/10g | nd | - |

dw: dry weight, nd: not detected, *: detection limit provided by method

Electrical conductivity (EC) was 2.55 ± 0.02 mS/cm, similar to the range reported by Nguyen et al. (2.12–3.19 mS/cm) [12], and below the microbial inhibition threshold (4–6 mS/cm). According to Bernal et al. [11] and Zucconi et al. [13], EC values below 4 mS/cm favor microbial activity and ensure compost safety for plants, indicating that COIMEX sludge is suitable for composting without salinity concerns.

Nutrient content was also favorable. Total nitrogen (4.26% dw) exceeded typical municipal sludge values (1.5–4%) [8, 10] and was comparable to seafood sludge reported in other studies (1.96–5.62%) [7, 12]. Total phosphorus was 2.72% dw, higher than Vo's study (1.15%) [7], confirming that the sludge is a valuable source of nutrients for composting.

However, fat, oil, and grease (FOG) content was 8005 mg/kg dw (8% dw), exceeding the QCVN threshold of 1000 mg/kg dw by more than eight times. This classifies the sludge as hazardous under Vietnamese standards. Compared with urban sludge, which typically contains 100–600 mg/kg dw [10, 14], the FOG level is markedly higher, reflecting the protein- and lipid-rich nature of seafood effluents.

Villar et al. [6] investigated seafood-processing sludge from a frozen seafood production facility in Spain and reported fat contents of approximately 19.8% dw, equivalent to 198,000 mg/kg dw—far higher than the COIMEX sample. Even after composting, their static treatment retained fat content of 8.0% dw (80,000 mg/kg dw) after 112 days, while turned composts reached 4.2% dw. These findings highlight that seafood sludge globally tends to have high FOG levels, reinforcing the necessity for specific treatment or pre-treatment measures prior to land application or composting.

Although classified as hazardous due to high FOG, this parameter is amenable to reduction through pre-treatment such as oil skimming, addition of bulking agents with high porosity (straw, sawdust), or use of biosurfactants. Thus, the sludge still holds potential for safe reuse after adequate treatment [6, 9, 15].

High FOG levels in sludge can adversely affect composting performance by coating bulking particles, reducing porosity and oxygen transfer, and generating unpleasant odors. Moreover, excessive lipids slow microbial degradation as hydrolysis of fats is often the rate-limiting step. Therefore, bulking agents with high structural porosity (rice husks, straw) are necessary to counterbalance these effects and maintain aerobic conditions [6, 10, 14].

Composting represents a promising integrated adsorption–biodegradation system, particularly for lipid-rich and pollutant-laden sludge. Research has shown that composting sludge can convert hazardous organic contaminants into stable, nutrient-rich materials while inactivating pathogens and reducing environmental impact [16]. Barker & Bryson et al. [17] further demonstrate that composting promotes the degradation of xenobiotics through microbial activity, while simultaneously binding heavy metals to organic components, thereby decreasing their bioavailability. Studies with lipid-rich wastes (e.g. animal fats, industrial foams) report substantial fat removal (up to ~80–85%) under thermophilic composting (60–70 °C), along with effective pathogen control [15]. Additionally, composting of oil and grease sludge has been proposed as a cost-effective bioremediation strategy when combined with suitable bulking agents and microorganisms that facilitate pollutant transformation [9, 10, 14].

The analysis of heavy metals, toxic inorganic and organic compounds, and microbiological indicators (Table 2) reveals that the sludge from the COIMEX seafood processing wastewater treatment system exhibits low levels of contamination and is suitable for reuse purposes. Most hazardous heavy metals such as As, Cd, Pb, Co, Ni, Se, and Hg were not detected (nd), suggesting that the sludge is not polluted by industrial or hazardous wastewater sources. Only barium (Ba) at 66.7 mg/kg dw and zinc (Zn) at 130.9 mg/kg dw were quantified, both far below the regulatory thresholds set by QCVN 50:2013/BTNMT (2000 and 5000 mg/kg dw, respectively). These findings are consistent with previous studies, including Huynh [18], where most heavy metals in fish processing sludge were found at low levels, although Zn showed a wider range (80–450 mg/kg dw).

Regarding toxic compounds, parameters such as Cr(VI), $CN^-$, phenol, and benzene were below detection limits, in contrast to urban or slaughterhouse sludge where such contaminants are commonly detected due to industrial additives or fuel residues [8, 10]. This confirms that COIMEX sludge is composed primarily of natural organic matter, with little to no contamination from synthetic chemicals or industrial byproducts.

Microbiological analysis revealed moderate levels of coliforms (7900 ± 121 MPN/100 mL) and *E. coli* (608 ± 28 MPN/100 mL), values that are typical of biological sludge containing decomposed organic matter [19]. Importantly, *Salmonella* spp. was not detected, which represents a significant advantage for composting applications because its absence reduces sanitary risk [19, 20]. Compared with Huynh's findings [18], the pathogenic microbial loads in COIMEX sludge were similar or lower, reflecting effective wastewater treatment and good control over input quality at the plant. Although these indicators require control before reuse, thermophilic composting (>55 °C for several consecutive days) has been documented to effectively inactivate pathogens such as *E. coli* and coliforms, thereby ensuring sanitary safety [20]. With adequate process management, microbiological risks associated with COIMEX sludge can therefore be effectively mitigated.

Preliminary composting trials conducted by our group with COIMEX sludge and agricultural residues demonstrated feasibility [21]. Three treatments were tested: BR (sludge:straw=1:0.3), BV (sludge:rice husks=1:0.32), and BH (sludge:straw:rice husks=1:0.18:0.15). The BH treatment reached thermophilic temperature by day 6, peaking at 57 °C, and maintained >55 °C for 3 days. Organic matter decreased by 54.1% and the Germination Index reached 84.7%, confirming compost maturity and phytotoxicity-free status. These results strongly support the feasibility of co-composting COIMEX sludge with bulking agents.

At pilot scale, composting can be implemented using aerated static piles or turned windrows to improve aeration and odor control [9, 10, 16]. Main costs are related to bulking agents and aeration; however, agricultural residues are abundant and low-cost in Vietnam, enhancing economic feasibility. Thus, COIMEX sludge offers potential as a feedstock for composting within circular economy models, provided that pre-treatment and process optimization are applied.

In summary, the low concentrations of heavy metals and toxic compounds, coupled with the absence of key pathogens, suggest that COIMEX sludge meets the essential safety criteria for composting applications. This supports its potential use in circular economy models for sustainable seafood waste management.

## Conclusion

The sludge from the COIMEX seafood processing wastewater treatment plant is characterized by high organic matter, nitrogen, and phosphorus contents, making it a promising raw material for composting. Although its FOG concentration significantly exceeds national thresholds for non-hazardous waste, this limitation can be mitigated through pre-treatment or co-composting with bulking agents. Heavy metals and toxic organic compounds were largely undetected, and microbiological risks can be effectively managed under thermophilic composting conditions. Importantly, the composting process not only stabilizes nutrients but also enhances biodegradation of organic pollutants, reduces odor, and contributes to the safe treatment of contaminants. These findings provide a scientific basis for promoting sludge composting as part of Vietnam's circular economy. Further pilot-scale and long-term studies are recommended to optimize process parameters and validate large-scale application.

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