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RESEARCH ARTICLE

Evaluating the performance of the wastewater treatment plant in intensive whiteleg shrimp (*Litopenaeus vannamei*) brackishwater pond aquaculture

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Abstract

Intensive technology of whiteleg shrimp (*Litopenaeus vannamei*) aquaculture generates wastewater that, if not properly managed, can adversely affect the long-term viability of brackishwater pond aquaculture and threaten environmental sustainability. This study evaluates the performance of wastewater treatment plant (WWTP) associated with this intensive whiteleg shrimp aquaculture. Wastewater samples were collected from various locations: the reservoir, grow-out pond, WWTP inlet, WWTP, WWTP outlet, and the sea, at four stages of shrimp growth (15, 45, 75, and 105 days of culture (DOC)). Key variables analyzed included temperature, salinity, pH, dissolved oxygen (DO), ammonia (NH_3), nitrate (NO_3), nitrite (NO_2), phosphate (PO_4), total organic matter (TOM), biochemical oxygen demand 5-day (BOD_5), and total suspended solids (TSS). Data from the WWTP inlet and outlet were used to assess removal efficiency (RE) and calculate compliance index (CI) values for evaluating WWTP performance. The Storage and Retrieval (Storet) system was used to evaluate the wastewater quality status. The results indicated that the WWTP utilized constructed wetlands with a hydrological design that included both surface and subsurface flow. On the culture of 105 DOC, the concentrations of NH_3, NO_3, and PO_4 at the WWTP outlet surpassed the threshold for marine and brackishwater aquatic life. However, the levels of pH, DO, NO_2, TOM, BOD_5, and TSS were within the acceptable range for marine and brackishwater aquatic life. The WWTP covered 9.51% of the total pond area, with a wastewater residence time of 0.76 days (18 h). It was effective in reducing TSS concentration (RE 60.05%) and demonstrated moderate effectiveness in lowering concentrations of NO_3 (RE 58.71%), NO_2 (RE 51.48%), PO_4 (RE 49.85%), and BOD_5 (RE 41.15%). The WWTP significantly reduced levels of NO_2, TOM, BOD_5, and TSS while raising the pH, achieving a compliance rating (CI < 1.00). Initially, the wastewater quality at the WWTP inlet was classified as class D (poor or heavily polluted), but changed to class C (moderate or moderately polluted) by 75 and 105 DOC. However, NH_3, NO_3, and PO_4 levels still exceeded acceptable limits for shrimp aquaculture. Overall, WWTP is successful in enhancing the quality of wastewater from intensive whiteleg shrimp brackishwater pond aquaculture. However, it has shown limited effectiveness in improving the levels of specific pollutants like NH_3, NO_3, and PO_4. To improve the system's efficiency, it is suggested to expand the WWTP area to 3.22 ha, increase the residence time to a minimal of 2 days, and add an aeration and equalization ponds to the system.

Keywords Brackishwater pond · Compliance index · Intensive technology · Removal efficiency · Wastewater quality status · Wastewater treatment plant · Whiteleg shrimp

Introduction

Crustacean aquaculture remains a vital component of the global aquaculture industry, contributing approximately 10 million tons of production in 2020. Notably, whiteleg shrimp (*Litopenaeus vannamei*) accounted for 52.9% of the total shrimp production worldwide (FAO 2020). Whiteleg shrimp leads the shrimp aquaculture industry because of

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Extended author information available on the last page of the article

its high tolerance to salinity, widely distributed and exhibiting robust environmental adaptability, fast growth rate, and desirable flavor (Fadel et al. 2025a,b). This shrimp variety is highly sought after in Indonesia and other countries, including China, the USA, Japan, India, and Ecuador (Zhang et al. 2015). By 2021, Indonesia shrimp brackishwater pond area was projected to reach around 562,000 ha, with 93% (522,600 ha) employing traditional or semi-traditional methods, and the remaining 7% (39,400 ha) utilizing semi-intensive, intensive, or super-intensive technologies (Utami et al. 2021). Given the significant market potential, efforts to enhance shrimp aquaculture in Indonesia are being pursued through the adoption of various technologies, management practices, and systems among business units. One approach involves implementing intensive technology, where whiteleg shrimp are raised at high stocking densities in controlled ponds (Mishra et al. 2008; Mohammadi et al. 2023).

Intensification in whiteleg shrimp aquaculture demands that practitioners utilize large amounts of feed, substantial oxygen supplies, and the use of chemicals (Engle et al. 2017; Syah et al. 2017; Emerenciano et al. 2022; Nisar et al. 2022; Mustafa et al. 2023, 2024b,c). Consequently, wastewater in the form of organic matter (OM) and inorganic compounds accumulates, including from feces, excess feed, the decomposed organism remains (shrimp and algae dead), and molted exoskeletons (Paena et al. 2020; Tom et al. 2021). However, the capacity of the brackishwater pond ecosystem to provide wastewater processing services is limited and once it exceeds that point, the wastewater products must be disposed of in a certain way. The wastewater generated within these whiteleg shrimp aquaculture systems exists in solid forms (sediments) like sludge or compounds dissolved in water, such as OM, ammonia (NH_3), nitrate (NO_3), nitrite (NO_2), hydrogen sulfide (H_2S), and phosphorus (P) (Iber and Kasan 2021; Tom et al. 2021; Mustafa et al. 2022, 2024b,c; Marzuki et al. 2023). Wastewater is all waste materials in liquid form, which may contain pathogenic microorganisms, toxic chemicals, and radioactivity (SME 1995; Abidar et al. 2020). Wastewater from whiteleg shrimp aquaculture activities in the brackishwater pond aquaculture occurs during the grow-out process from pond preparation to harvest. The release of raw and improperly treated wastewater onto water courses has both short- and long-term effects on the environment. Water exchange increases water use, increases the risk of escape and spreading infectious disease, and transfers the ecological and economic burden of wastewater from inside the pond to other water bodies, which has ethical repercussions and may be subject to legal regulations (Boyd et al. 2020). The environmental impacts of shrimp aquaculture include the destruction of wetland habitats, such as mangrove forests; the spread of chemicals and nutrients into the environment; depletion and biological pollution of wild fish and shrimp populations; and the decline of wild aquatic habitat species (Henares et al. 2019). This practice reiterates the report published by IWA (2018) that about 80% of all wastewater is discharged into the world's waterways.

Reports of environmental pollution from whiteleg shrimp aquaculture have emerged in various locations across Indonesia. In Kwanyar District, Bangkalan Regency, East Java Province, wastewater from intensive whiteleg shrimp aquaculture has resulted in elevated levels of biochemical oxygen demand 5-day (BOD_5), chemical oxygen demand (COD), and NH_3 that exceed acceptable thresholds for marine life (Huda 2018). Additionally, Muqsith et al. (2019) noted that in the coastal area of Banyuputih District, Situbondo Regency, the concentrations of total suspended solids (TSS) and COD also surpassed limits harmful to marine organisms and shrimp due to similar wastewater discharges. Furthermore, Harianja et al. (2018) reported high levels of BOD_5, NO_3, and phosphate (PO_4) in Sungai Kembung, Bantang District, Bengkalis Regency, Riau Islands Province, which is affected by wastewater from intensive whiteleg shrimp aquaculture.

The volume of wastewater generated is influenced by the size of the pond, the technology used in barckishwater pond aquaculture, and management practices. Larger pond areas and advanced technologies lead to higher wastewater discharges into coastal regions. Therefore, accurately assessing the wastewater output from whiteleg shrimp aquaculture at various technological levels and pond sizes is crucial (Muqsith et al. 2019; Iber and Kasan 2021). For super-intensive whiteleg shrimp aquaculture, the wastewater released into the aquatic environment contains between 43.09 and 50.12 kg of total nitrogen (TN)/ton of shrimp produced, and 14.21 to 15.73 kg of total phosphate (TP)/ton of shrimp produced (Syah et al. 2014). Effective management, particularly regarding feed, also affects wastewater generation. The extent of the impact varies based on the aquaculture system, commodity type, water management practices (including frequency and volume of water changes), stocking density, feed quality and quantity, as well as coastal conditions (Syah et al. 2017; Araujo et al. 2022). To reduce the wastewater output from whiteleg shrimp aquaculture, implementing a wastewater treatment plant (WWTP) is a viable solution, ensuring that discharged water meets quality standards and supports sustainable whiteleg shrimp aquaculture. WWTP involves processes designed to enhance wastewater quality and mitigate its adverse effects on human health (Akuma et al. 2022). It is essential to treat wastewater to high standards before its release into the environment or for reuse (Feng et al. 2022). In super-intensive whiteleg shrimp aquaculture, WWTP have been designed to address issues related to high levels of TSS, TN, total organic matter (TOM), and BOD_5, as well as low pH and dissolved oxygen (DO) levels (Syah et al. 2017).

Syah et al. (2017) and Mangarengi et al. (2019) assess the performance of WWTP in whiteleg shrimp brackishwater ponds aquaculture utilizing super-intensive technology by measuring removal efficiency (RE). This study evaluates the performance of the WWTP in the context of intensive technology whiteleg shrimp aquaculture. Unlike previous studies, it considers not only the RE but also the compliance index (CI) and the overall wastewater quality status. To assess the WWTP performance, tests conducted by Quadros et al. (2010), Vítěz et al. (2012), and Nikuze et al. (2020) incorporate both RE and CI. Additionally, Mustafa et al. (2022, 2024b,c) analyze the performance of WWTP in intensive whiteleg shrimp aquaculture by examining the wastewater quality status. Ramos et al. (2009) have conducted a study of the effectiveness of WWTP on a laboratory scale using sedimentation and the filtration process of *Crassostrea gigas* and *Crassostrea rhizophorae* oysters. The use of sedimentation treatment in WWTP has been researched for whiteleg shrimp and blue shrimp (*Penaeus stylirostris*) aquaculture (Teichert-Coddington et al. 1999).

The different states of the arts discussed indicate that this study will yield something new. This innovation pertains to the performance of the WWTP in intensive whiteleg shrimp aquaculture and the alternative development of the current WWTP.

South Sulawesi Province is a key area for shrimp aquaculture in Indonesia's brackishwater ponds. As of 2015, it ranked eighth in the country's whiteleg shrimp production (MMAF 2016b). By 2019, the total area of brackishwater ponds aquaculture in the province had reached 108,465 ha (FMS 2020), utilized for traditional (including traditional plus), semi-intensive, and intensive (including super-intensive) technologies, which occupied 102,277 ha, 5,490 ha, and 698 ha, respectively. Among the intensive technology shrimp aquaculture areas, 469.80 ha (67.33%) are located on the southern coast, including Bulukumba Regency. These ponds draw and release water from the Flores Sea, influenced by water exchanges with the Pacific Ocean through the Sulawesi, Flores, and Java Seas. This interaction boosts primary productivity in the waters south of the Makassar Strait (Silaban et al. 2021), contributing to the dynamic nature of these waters, which is vital for fisheries due to nutrient enrichment (Samad et al. 2018). The Taka Bonerate National Park, situated in the Flores Sea, was designated United Nations Educational, Scientific and Cultural Organization (UNESCO) Biosphere Reserve in 2015 (UNESCO 2022). Located in the Selayar Islands Regency, it covers 530,765 ha, with 220,000 ha being the largest atoll in Indonesia and Southeast Asia, and the third largest globally, following Kwajalein Atoll (Marshall Islands) and Suvadiva Atoll (Maldives) (Garniati et al. 2019). However, areas around atolls face threats such as pollution, nutrient overload, alterations from construction activities (like dredging and landfilling), and extensive resource exploitation (Fabricius 2005; Riegl et al. 2012; D'Angelo and Wiedenmann 2014).

This study focuses on evaluating the performance of WWTP used in intensive technology whiteleg shrimp aquaculture. The goal is to analyze how effectively these systems treat wastewater and identify areas for improvement. By understanding the strengths and weaknesses of the current WWTP performance, the findings aim to serve as a reference for optimizing treatment processes, ultimately minimizing wastewater and its environmental impact from shrimp aquaculture.

Materials and methods

Time and location study

The study was carried out in 2023 and 2024. This study was carried out at one of the intensive technologies whiteleg shrimp aquaculture, PT XYZ, located on the south coast of South Sulawesi Province, namely in Gantarang District, Bulukumba Regency, South Sulawesi Province, Indonesia (Fig. 1).

Data collection

Evaluating the performance of WWTP involves analyzing several factors: (a) the RE of the WWTP (Syah et al. 2017; Mangarengi et al. 2019), (b) the CI of the WWTP (Quadros et al. 2010; Vítěz et al. 2012; Nikuze et al. 2020; Ramkumar et al. 2022), and (c) the quality of wastewater after it has been treated by the WWTP (Mustafa et al. 2022, 2024b).

Seawater is drawn from Flores Sea using water pumps and stored in a reservoir (Reservoir). From there, it is pumped into grow-out pond (Pond) where whiteleg shrimp are reared. When the water needs to be replaced, it is drained from the grow-out pond by gravity and directed through a canal (the WTTP inlet, Inlet) to the WWTP itself (WWTP). Water flows by gravity from one part of the WWTP to another, and then continues by gravity to the WWTP outlet (Outlet), before finally discharging into the sea (Sea), namely Flores Sea (Figs. 1 and 2).

Wastewater samples were collected from various locations: the reservoir, the grow-out pond, the WWTP inlet, the WWTP, the WWTP outlet, and the sea (Figs. 1 and 2). In this study, all samples are considered wastewater, with some specifically identified as raw wastewater—those that have not been treated to remove contaminants, such as those from the reservoir, pond, and inlet. The sampling distribution included two samples from the reservoir, two from the grow-out pond, two from the WWTP inlet, two from the WWTP, two from the WWTP outlet, and two from the sea. The sampling locations follow the wastewater flow pattern

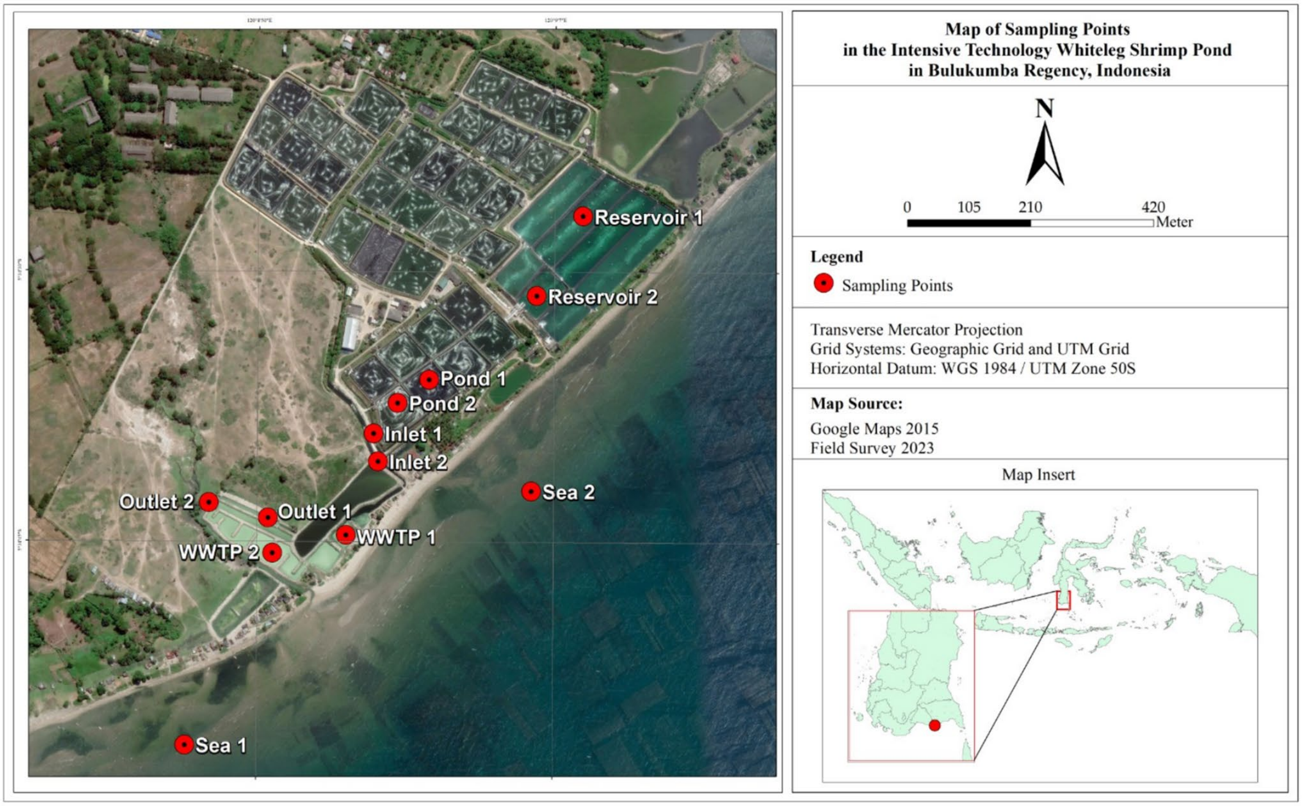

Fig. 1 Study location and points sampling of wastewater in the intensive technology whiteleg shrimp aquaculture in Gantarang District, Bulukumba Regency, South Sulawesi Province, Indonesia

in the brackishwater pond area. Each sampling involved collecting two points, which were then composited. Samples were taken monthly during intensive whiteleg shrimp aquaculture, specifically at 15, 45, 75, and 105 days of culture (DOC). Preservation of the wastewater samples adhered to APHA (2012) guidelines. The samples were sent to the Water Laboratory of the Research Institute for Coastal Aquaculture and Fisheries Extension in Maros Regency, South Sulawesi Province for analysis. The quality variables examined included NH_3, NO_3, NO_2, PO_4, total organic matter (TOM), BOD_5, and TSS, with specific methods for each: NH_3 by the phenate method, NO_3 by sodium reduction, NO_2 by colorimetry, PO_4 by ascorbic acid, TOM by titrimetry, BOD_5 by Winkler titration, and TSS by gravimetry, all according to APHA (2012). Additional parameters like temperature, salinity, pH, and dissolved oxygen (DO) were measured directly in the field using a YSI Pro Plus meter. Sampling and measurements were conducted between 08:30 and 10:30 local time.

Additional primary data consisted of brackishwater pond profiles for whiteleg shrimp, gathered from records maintained by shrimp farm managers and from direct observations at the brackishwater ponds. Furthermore, data was gathered using a structured questionnaire distributed to selected respondents, specifically the managers involved in intensive whiteleg shrimp aquaculture.

Additional primary data for understanding land cover and land use is sourced from Sentinel-2 satellite imagery (10.0 m spatial resolution) and SPOT (*Satellite pour l'Observation de la Terre*) 7 (1.5 m spatial resolution). This data was obtained from the Remote Sensing Earth Station at the National Institute of Aeronautics and Space (*Lembaga Penerbangan dan Antariksa Nasional, LAPAN*), the National Research and Innovation Agency, NRIA (*Badan Riset dan Inovasi Nasional, BRIN*) in Parepare City, South Sulawesi Province. The Sentinel-2 and SPOT-7 images for Bulukumba Regency were collected on 8 February 2021 and 5 March 2021, respectively.

Data analysis

Satellite imagery from Sentinel-2 and SPOT-7 was classified with Er Mapper 7.0 and Arc GIS 10.2, and then combined with *Rupabumi Indonesia* (RBI) Maps to create land use maps, including those for brackishwater ponds. These two satellite images helped calculate the size of the reservoir, the grow-out pond, and the WWTP using the same software.

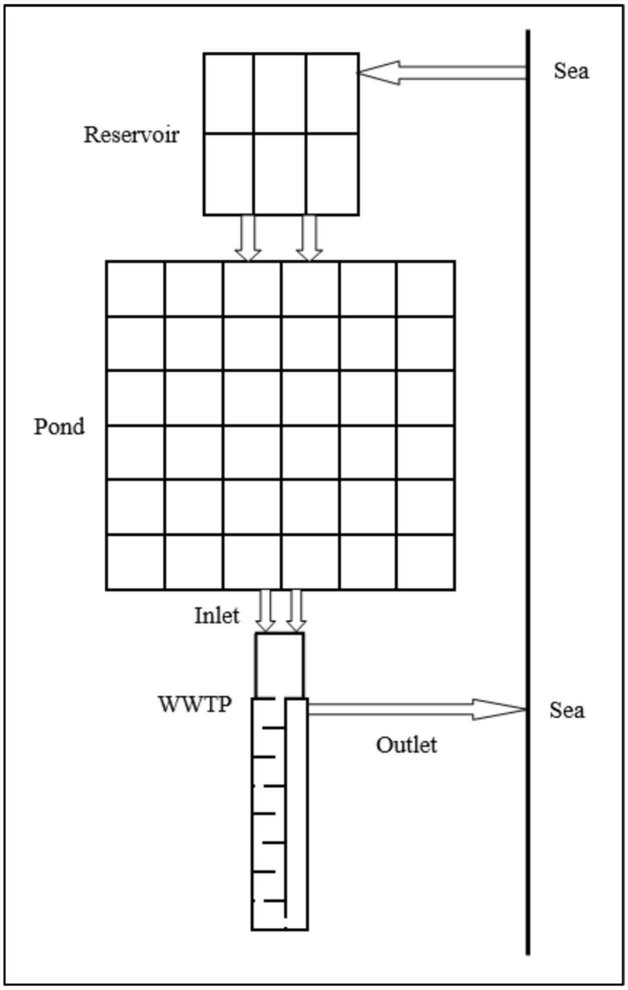

Fig. 2 Illustration of the wastewater movement in intensive technology whiteleg shrimp aquaculture ponds

Data analysis utilized descriptive statistics to identify the minimum, maximum, average, standard deviation, and standard error for each wastewater quality variables. A two independent sample *t*-test was conducted using Statistical Product and Service Solutions (SPSS) version 25 to assess differences in water quality variables between the inlet and outlet of the WWTP for intensive whiteleg shrimp aquaculture. Before the independent sample *t*-test was applied, Levene's test was applied to check for homogeneity of variance and the Kolmogorov–Smirnov test was used to assess the normality of the data distribution (Faizi and Alvi 2023). Common assumptions for the *t*-test include considerations related to the measurement scale, random sampling, normality of data distribution, adequate sample size, and equal variances in standard deviation (Kim and Park 2019).

The wastewater quality analysis results were compared to the standard values for water quality variables outlined in several regulations, including the Minister of the Environment Decree Number 51 of 2004 about the Standard Quality of Seawater for Marine Organisms (SME 2004), the Ministry of Marine Affairs and Fisheries Regulation Number 75/Permen-KP/2016 about General Guidelines for Grow-out of Tiger Shrimp (*Penaeus monodon*) and Whiteleg Shrimp (*Litopenaeus vannamei*) (MMAF 2016a), and the Bangka Belitung Islands Governor Regulation Number 34 of 2019 about Guidelines for Controlling Surface Water Pollution for Shrimp Aquaculture (Government of Bangka Belitung Island Provincial 2019).

The RE of a WWTP is determined using Eq. 1, as proposed by Vítěz et al. (2012):

$$RE = \frac{\left(C_{in} - C_{out}\right)}{C_{in}} \times 100 \quad (1)$$

where.

RE: removal efficiency of WWTP.

C_{in}: the value of wastewater variables in the WWTP inlet.

C_{out}: the value of wastewater variables in the WWTP outlet.

The RE level category for WWTP is based on Tchobanoglous and Burton (1991) classification: very efficient is when RE is greater than 80%; efficient ranges from 60 to 80%; quite efficient is between 40 and 60%; less efficient falls between 20 and 40%; and inefficient is when RE is below 20%.

The CI is a statistical measure that provides a quick assessment of a WWTP performance. A CI value below 1.00 signifies adherence to established standards, whereas a value of 1.00 or higher indicates non-compliance (Vítěz et al. 2012; Nikuze et al. 2020). The CI for each variable is determined using Eq. 2 (Quadros et al. 2010; Vítěz et al. 2012; Nikuze et al. 2020):

$$CI = \frac{V}{S} \times 100\% \quad (2)$$

where.

CI: compliance index of WWTP.

V: the value of wastewater variables.

S: the standard value of wastewater variables.

The Storage and Retrieval (Storet) system was utilized to assess wastewater quality status. The evaluation scores were derived from Canter (1982), which considered both the number of variables and physical and chemical factors (see Table 1). Water quality was classified into four categories: (a) score $= 0$: class A, excellent and meeting quality standards; (b) score between -1 and -10: class B, good but slightly polluted; (c) score between -11 and -30: class C, moderate and moderately polluted; and (d) score ≤ -31: class D, poor and heavily polluted (SME 2003).

Table 1 The scoring system used to determine the water quality status of wastewater of whiteleg shrimp brackishwater pond aquaculture

Number of variables	Score	Variables		
		Physical	Chemical	Biological
< 10	Maximum	− 1	− 2	− 3
	Minimum	− 1	− 2	− 3
	Average	− 3	− 6	− 9
≥ 10	Maximum	− 2	− 4	− 6
	Minimum	− 2	− 4	− 6
	Average	− 6	− 12	− 18

Source: Canter (1982)

Results and discussion

Performance of brackishwater pond and shrimp production

Intensive technology whiteleg shrimp aquaculture in Bulukumba Regency takes place in two districts: Bonto Bahari and Gantarang. Within Gantarang, three businesses employing intensive technology shrimp aquaculture are operational, including PT XYZ. Established in 2004, all of PT XYZ's ponds (both reservoir and grow-out) are lined with high-density polyethylene (HDPE) (Table 2). The use of HDPE lining allows for high production rates and is suitable for areas with high porosity, sandy soils, and mineral acid soils, such as acid sulfate soil (Mustafa et al. 2022; Tarunamulia et al. 2024). Additionally, these HDPE-lined ponds exhibit low levels of total ammonia–nitrogen (TAN) and a rich presence of plankton (Casé et al. 2008; Satanwat et al. 2023). The grow-out ponds size range from 3000 to 6000 m^2, totaling 35 ponds. The size of the grow-out ponds is influenced by the shrimp aquaculture technology used, with those employing intensive technology generally being larger than those using super-intensive technology. Land availability also affects pond size. For instance, Syah et al. (2017) utilized 1000

Table 2 Performance of intensive technology whiteleg shrimp brackishwater pond aquaculture

Variables	Value
Constructed year	2014
Operationalized year	2015
Grow-out pond construction	HDPE
Reservoir construction	HDPE
Wastewater treatment plant construction	Soil
Pond shape	Square
Height of dike (m)	2.5–3.0
Reservoir area (ha)	4.71
Wastewater treatment plant area (ha)	1.53
Total volume of wastewater treatment plant (m^3)	12,240
Pond number (unit)	35
Pond area (m^2)	3000–6000 (4600)
Total pond area (ha)	16.08
Reservoir area to total pond area (%)	29.28
Wastewater treatment plant area to total pond area (%)	9.51
Effluent volume (m^3/day)	16,080
Residence time of pond effluent in wastewater treatment plant (days)	0.76
Stocking density (ind./m^2)	270–300
Partial harvest time (DOC)	60–90
Partial harvest size (ind./kg)	50–80
Total harvest time (DOC)	120–134
Total harvest size (ind./kg)	20–30
Total production (tons/ha/cycle)	59.0
Survival rate (%)	91
Feed conversion ratio	1.2:1–1.8:1
Prediction of total N waste load (tons/cycle)	13.13
Prediction of total P waste load (tons/cycle)	7.67
Problems experienced during culture	Intermittent electrical supply and disease attacks

m^2 ponds for super-intensive technology shrimp aquaculture in Takalar Regency, South Sulawesi Province while Tantu et al. (2020) worked with 1000 and 1600 m^2 ponds in Barru Regency, South Sulawesi Province. According to Islam et al. (2005) and Ahmed et al. (2023), smaller ponds are often easier to manage and yield higher shrimp productivity compared to larger ones.

Stocking density ranges from 270 to 300 ind./m^2, depending on the level of technology used, specifically intensive technology. According to Wasielesky et al. (2013), a density of 60–300 ind./m^2 is considered high for intensive shrimp aquaculture. For whiteleg shrimp raised using intensive technology, the stocking density falls between 100 and 500 ind./m^2 (Irani et al. 2023).

Maintaining water quality is crucial for whiteleg shrimp aquaculture to ensure a consistently high standard of water for their growth. One effective approach to managing water quality is utilizing a reservoir (Mustafa et al. 2023, 2024b). This reservoir supplies appropriate water for shrimp aquaculture, and it is necessary to start with reservoir water and continue replacing or adding it throughout the aquaculture process to sustain the brackishwater pond's capacity (Syah et al. 2014). The reservoir covers an area of 4.71 ha, making up 29.28% of the total pond area (Table 2). An effective reservoir should provide 30% of the water volume needed in the brackishwater ponds aquaculture, be situated near the water source, and facilitate easy distribution.

The WWTP is a crucial component of managing wastewater in brackishwater ponds aquaculture (Syah et al. 2017; Mangarengi et al. 2019; Mustafa et al. 2023, 2024b). Its primary aim is to prevent wastewater from whiteleg shrimp aquaculture from polluting the environment and to facilitate its reuse for brackishwater pond aquaculture. Field observations indicate that the WWTP includes constructed wetlands, which are cost-effective and ecological systems capable of functioning without chemicals or electricity, while also avoiding issues with sludge disposal (Gupta et al. 2020; Waly et al. 2022). However, these systems are relatively slow and require a large land area, likely due to the prevalence of anaerobic processes that involve rate-limiting reactions stemming from the limited availability of suitable electron acceptors for pollutant oxidation (Gupta et al. 2020; Su et al. 2023). Constructed wetlands can be classified based on various design factors, with three key criteria being hydrology (surface and subsurface flow), macrophyte growth forms (emergent, submerged, free-floating, and floating-leaved plants), and flow paths (horizontal and vertical) (Vymazal 2007, 2008). The WWTP designed for intensive whiteleg shrimp aquaculture in Bulukumba Regency falls under the hydrology category, specifically water surface and subsurface flow. Essentially, constructed wetlands are engineered systems that harness natural processes involving wetland plants, soils, and associated microbes to treat wastewater. Terms synonymous with "constructed" include "man-made," "engineered," or "artificial" (Vymazal 2007). The WWTP covers an area of 1.53 ha, representing 9.51% of the total pond area (Table 2). It consists of ten interconnected ponds, ranging in size from 0.07 to 0.24 ha, arranged in a zig-zag configuration (Fig. 2). DGA (2019) recommends that WWTP occupy at least 20% of the total pond area for intensive whiteleg shrimp technology. In Vietnam, intensive whiteleg shrimp aquaculture is required to have a minimum WWTP facility of 0.25 ha for every 1.0 ha of growout ponds, which equates to 25% of the total pond volume (Nguyen et al. 2019).

Additionally, WWTP has a short residence time for wastewater, averaging only 0.76 days (or 18 h), due to the continuous flow by gravity (see Table 2). This limited residence time diminishes the effectiveness of the WWTP. For wastewater generated by intensive whiteleg shrimp aquaculture, a minimum residence time of 2 days is recommended (Syah et al. 2017; DGA 2019). Inadequate management of wastewater discharge poses health, environmental, and climate risks, affecting the water's ability to assimilate waste (Teichert-Coddington et al. 1999).

Farmers typically use two harvesting methods: partial harvest and total harvest. Partial harvest involves removing only a portion of the shrimp from the pond while leaving the remainder to grow until they reach a certain age. This method is especially effective in high-density technology systems, such as intensive technology whiteleg shrimp aquaculture, where there are many shrimp present. The goal of partial harvest is to decrease stocking density, which helps lower the risk of disease transmission and maintain the pond environmental balance (Mustafa et al. 2022, 2023, 2024b). Additionally, partial harvesting can enhance productivity and profits, as the remaining shrimp grow larger by the end of the culture period. In the whiteleg shrimp aquaculture, the first partial harvest typically occurs between 60 and 90 DOC. The timing and frequency of these harvests depend on the biomass levels and water quality, particularly the concentration of DO, with a maximum of two partial harvests per cycle. There is no specific target for biomass harvested during a partial harvest, but the shrimp collected usually range from 50 to 80 ind./kg. Overall, partial harvesting can boost total production by promoting individual growth and survival while reducing competition (Brummett 2002; Anh et al. 2010).

The total harvest of whiteleg shrimp is reported when they reach 120–134 DOC. Their size can vary significantly, ranging from 20 to 30 ind./kg. The production in ponds primarily depends on factors such as stocking density, pond size, and any technical challenges encountered during cultivation, all of which can influence the growth and survival rate of the shrimp. On average, productivity is around 59.0 tons/ha/cycle.

Table 2 indicates that the ratio of the WWTP area to the total pond area is 9.51% resulting in whiteleg shrimp weights ranging from 33.3 to 50.0 g/ind. and a survival rate of 91% maintained over 120–134 DOC. These findings suggest that the growth and survival rate of the whiteleg shrimp are within normal ranges, which is further supported by the pond's water quality that continues to promote their growth and survival rate. At a stocking density of 750 ind./m^2 or super-intensive technology, Syah et al. (2017) achieved a whiteleg shrimp weight of 15.55 g/ind. and survival rate of 87.3% after cultured 105 DOC in a pond with a 45% WWTP area to pond area ratio. In intensive whiteleg shrimp brackishwater ponds aquaculture in Bulukumba Regency, South Sulawesi Province, weights between 16.9 and 38.5 g/ind. were recorded at stocking densities of 100–220 ind./m^2 after cultured 100–120 DOC, using a WWTP area to total pond area ratio ranging from 3 to 17% (Mustafa et al. 2022). The variations in WWTP area to total pond area ratio, stocking density, culture duration, and pond management applied contributed to differences in the weight and survival rate of whiteleg shrimp. The ratio of the WWTP area to the total pond area indicates the WWTP capacity to manage the waste generated by the pond (Darwin et al. 2021). A higher ratio suggests a greater capacity for wastewater processing, helping to maintain stable water quality and prevent pollution before discharge into the sea. With improved water quality, the growth and survival rate of whiteleg shrimp can be optimized. However, if the ratio is either too small or too large, it can negatively impact shrimp aquaculture. A small ratio may lead to the WWTP being unable to handle the waste effectively, while a large ratio could result in underutilized capacity. Therefore, it is crucial to optimize this ratio for the WWTP to function efficiently and support the success and sustainability of whiteleg shrimp aquaculture.

The feed conversion ratio (FCR) is defined as the weight of feed divided by the weight of shrimp produced, indicating how effectively shrimp convert feed into weight gain across various systems. The FCR typically ranges from 1.2:1 to 1.8:1 and is influenced by factors such as water quality, feeding frequency, stocking density, aeration, and feeding methods (Espinoza-Ortega et al. 2023). In a study by Ariadi et al. (2020), an FCR of 1.27:1 to 1.37:1 was recorded in intensive whiteleg shrimp aquaculture with a stocking density of 120 ind./m^2.

Study by Muqsith et al. (2019) revealed that in intensive whiteleg shrimp aquaculture ponds in Bulukumba Regency, TN wastewater production reached 13.13 tons/cycle, while TP reached 7.67 tons/cycle. The intensive whiteleg shrimp aquaculture was conducted in the coastal waters of Arungkeke District, Je'neponto Regency, with a stocking density of 250 ind./m^2 across 23 ponds, each covering 3600 m^2, these ponds have the potential to generate wastewater containing 7408 kg of TN and 1748 kg of TP/cycle (Mustafa et al. 2024b). The TN and TP generated in these systems primarily come from shrimp excretion and the breakdown of leftover feed, with approximately 60–90% N in dissolved forms (van Rijn 2013). From the feed provided to the shrimp, about 60–80% of N and 85–90% of P are lost as waste in the aquaculture water (Kawasaki et al. 2016). However, the settled wastewater from this intensive shrimp aquaculture can be repurposed as organic fertilizer. The solid waste from super-intensive whiteleg shrimp aquaculture contains 0.67% N, 4.78% P_2O_5, 1.00% K_2O, 17.48% organic C, and 15.60% water, and has a pH of 6.25 (Suwoyo et al. 2020).

Even though the productivity of whiteleg shrimp aquaculture ponds is relatively high, various problems are also found in this aquaculture, as presented in Table 2. In general, the problems in intensive technology whiteleg shrimp aquaculture ponds include intermittent electrical supply and disease attacks. Disease attacks are the biggest problem in intensive technology whiteleg shrimp aquaculture in Bulukumba Regency (Mustafa et al. 2024c). The disease that attacks whiteleg shrimp ponds is acute hepatopancreatic necrosis disease (AHPND), or generally known as early mortality syndrome (EMS). The clinical symptoms shown by the affected shrimp *Vibrio parahaemolyticus* (Vp_{AHPND}) bacteria include the following: emptying of the digestive tract, the hepatopancreas are pale and smaller, the skin becomes soft, and black spots on the hepatopancreas (Han et al. 2015). Vp_{AHPND} is a pathogen demonstrating remarkable adaptability, surviving across diverse temperatures, salinity levels, and pH conditions in estuarine and marine environments (Fadel et al. 2025a). New preventive strategies have been developed, including the use of probiotics, ozone nanobubbles, and consortia of microalgae and bacteria. Among these, natural by-products have shown notable potential as functional feed additives for controlling bacterial diseases in shrimp (Fadel et al. 2024a). Bioactive compounds derived from sources such as plants, algae, animals, bacteria, and yeast present promising alternative methods for managing bacterial infections. Moreover, Fadel et al. (2024a) also highlight the potential of bioactive compounds derived from fungi in managing AHPND in shrimp aquaculture.

Characteristics of wastewater

The characteristics of wastewater differ depending on the activity, necessitating various treatment processes. Wastewater quality is assessed through its physical, chemical, and biological attributes. Temperature plays a crucial role in the growth, survival rate, oxygen consumption, molting cycles, and immunity of shrimp (Ren et al. 2021) and influences the rate of biochemical reactions. The temperature of brackishwater pond water can be affected by its geographical location and local climate. Variations in temperature can result from factors like topography and water depth, which impact sunlight penetration. Water temperature is also subject to change based on the time and place of measurement (Fig. 3a and b), ranging from 26.1 to 31.7 °C. For marine organisms and intensive whiteleg shrimp aquaculture, the ideal water temperature is between 28 and 30 °C (MMAF 2016a). The lowest average temperature recorded in grow-out ponds was 28.1 °C, while the highest in the WWTP was 29.9 °C. The greater water depth in larger grow-out ponds, reaching up to 1.5–1.8 m, contributes to the lower temperatures in these brackishwater ponds. During the rearing of whiteleg shrimp, water temperatures increased from 15 to 75 DOC, which occurred in the dry season (August–October), before declining during the rainy season (November) at 105 DOC. As noted by Sriyasak et al. (2013) and Wiranegara et al. (2023), brackishwater pond water temperatures are generally higher in the dry season compared to the rainy season, with the elevated temperatures attributed to intense sunlight and wind affecting water distribution. Increased light intensity leads to greater heat absorption by the water, resulting in higher temperatures.

Salinity refers to the concentration of chloride ions in water. Whiteleg shrimp can tolerate a wide salinity range from 5 to 40 ppt, but their optimum conditions lie between 26 and 32 ppt (MMAF 2016a). They can adjust to gradual decreases in salinity; however, sudden changes exceeding 5 ppt can induce stress. Healthy salinity levels for marine organisms typically fall between 33 and 34 ppt (SME 2004). In a brackishwater pond where whiteleg shrimp were raised at 15 DOC, the initial salinity was lower due to their early development. Subsequently, salinity rose due to evaporation and then decreased again during the rainy season (Fig. 3c and d). The highest salinity recorded in grow-out ponds reached 42.45 ppt (Fig. 3d). The use of paddle wheels in these ponds increases the water surface area, which enhances evaporation. Larger water bodies experience more exposure to warm air, leading to increased evaporation rates and higher salinity. Elevated salinity levels demand more energy for shrimp osmoregulation, raising their metabolic rates and affecting their growth. This can result in slower growth rate, a higher FCR, and greater vulnerability to diseases (Liu et al. 2023).

The water quality variable that indicates whether water is acidic or alkaline is pH, which influences chemical reactions in ponds and affects the toxicity of harmful compounds like NH_3 and H_2S. Maintaining a stable pH is crucial for the metabolism and physiological health of shrimp. Various factors, including soil composition, rainfall, and biological activities such as phytoplankton respiration and photosynthesis, can affect pH levels (Hinga 2002). For intensive whiteleg shrimp aquaculture, optimum pH levels range from 7.5 to 8.5 (MMAF 20016a), while the pH suitable for sustaining biological life is relatively narrow, typically between 6.0 and 9.0. The results of Mangarengi et al. (2019) study on intensive technology whiteleg shrimp aquaculture ponds in Takalar Regency, South Sulawesi Province obtained a wastewater pH of 8.40 at the WWTP inlet and a pH of 8.72 at the WWTP outlet. The pH of the wastewater stays consistent during sedimentation and filtration in a laboratory-scale WWTP system used for whiteleg shrimp aquaculture (Ramos et al. 2009). Extreme pH levels can disrupt biological processes in treatment systems (Owhonka et al. 2021). Marine organisms thrives in water with pH levels between 7.0 and 8.5 (SME 2004). Notably, the highest pH levels during whiteleg shrimp aquaculture were recorded at 105 DOC, and the highest pH values were found in the sea (Fig. 3e and f). The average pH of surface seawater in Indonesia varies by location, ranging from 7.0 to 8.5 (Putri et al. 2015). Conversely, the lower pH observed in the wastewater at the WWTP inlet and within the WWTP is likely due to a high concentration of TOM (Fig. 5c and d). This lower pH is attributed to the decomposition of TOM, which generates acids—particularly in anaerobic conditions where complex compounds are broken down, resulting in the production of H_2S.

DO is another key factor influencing wastewater characteristics. It is essential for the respiration of shrimp and other organisms, including the microorganisms that break down OM in ponds. Various factors such as weather, paddle wheels, plankton populations, and microbial metabolism impact DO levels. It is one of the most crucial environmental variables that directly influence production and growth through metabolic processes and environmental conditions (Koyama et al. 2020). The DO concentration in water can significantly affect growth, FCR, and the carrying capacity of aquatic systems. The highest levels of DO are typically observed in grow-out ponds, where paddle wheels are used to enhance DO levels, thereby promoting the growth and survival rates of whiteleg shrimp.

In terms of water quality, nutrients are molecules in water that aquatic organisms can utilize for cell growth (Yildiz et al. 2017). Key nutrients for organisms like whiteleg shrimp include NH_3, NO_3, NO_2, and PO_4. As indicated in Table 2, the estimated TN waste from whiteleg shrimp aquaculture is 13.13 tons/cycle, with TP waste at 7.67 tons/cycle. The main source of NH_3 in shrimp aquaculture comes from both supplementary feed and the waste excreted by the cultured shrimp (Weldon et al. 2021). Typically, shrimp feed consists of 35 to 42% protein (dry weight), which is the primary source of NH_3. High levels of NH_3 can negatively affect shrimp growth and may lead to mortality. The concentration of NH_3 in pond systems is directly related to the amount of feed provided (Edwards et al. 2024). Low DO levels indicate high NH_3 levels, while high DO levels are associated with low NH_3 concentrations. Additionally, NH_3 in water is produced from the metabolism of aquatic organisms and the breakdown of OM by bacteria (Lemonnier

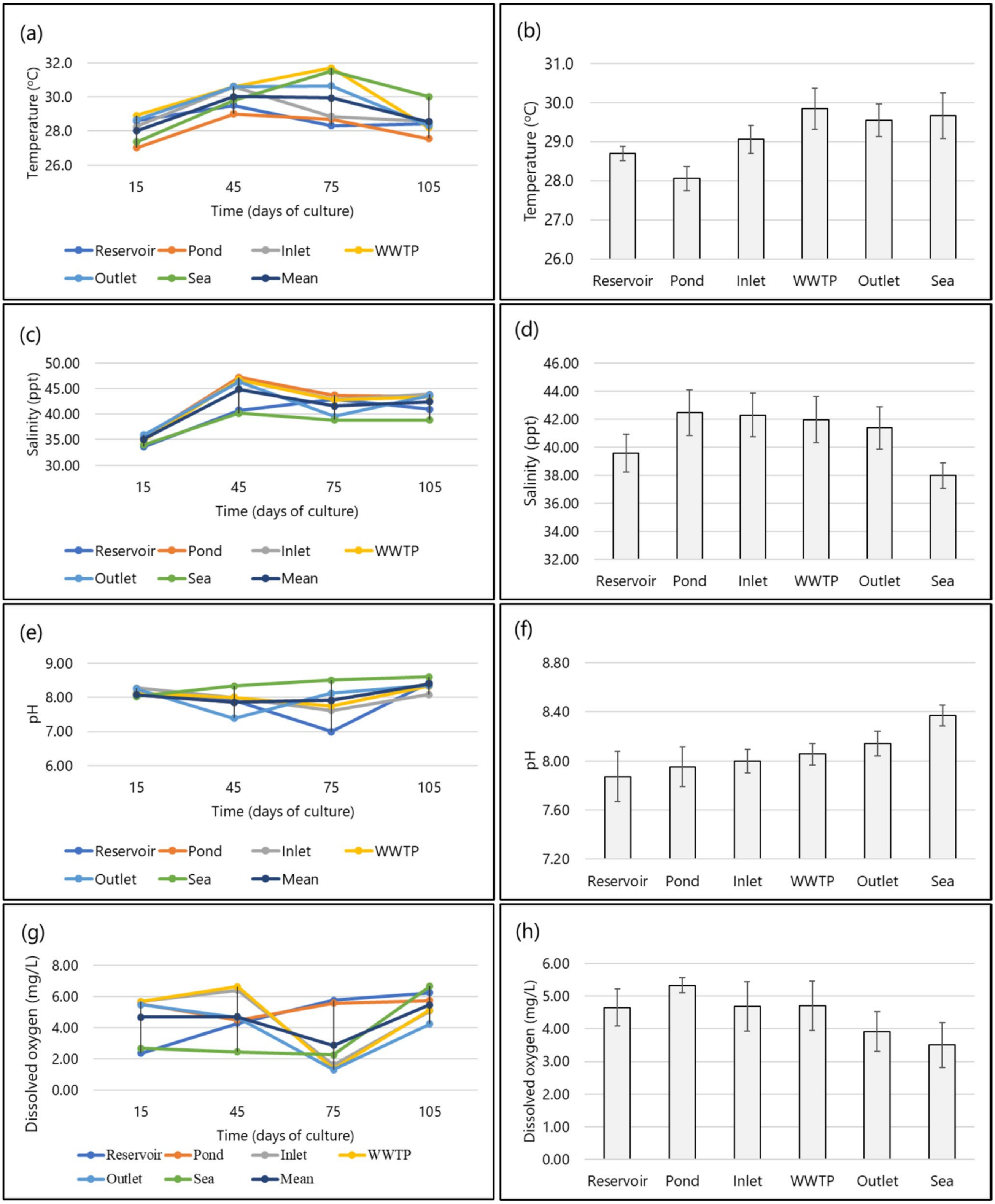

Fig. 3 Wastewater quality measured directly in the field at different times (left) and locations (right) in intensive technology whiteleg shrimp barackishwater pond aquaculture (**a**, **c**, **e**, **g** $n = 2$; **b**, **d**, **f**, **h** $n = 8$, average ± standard error)

et al. 2017; Lin et al. 2023). As illustrated in Fig. 4a, NH_3 concentration tends to rise with longer rearing periods for whiteleg shrimp. The elevated NH_3 levels from feed used in grow-out ponds are subsequently released through the WWTP inlet, leading to increased NH_3 concentrations in that area (Fig. 4b). Conversely, the lowest NH_3 levels were observed in the reservoir pond, where no feed is provided. N waste, such as NH_3, is connected to OM input and the NH_4 excretion from fish or shrimp (Sriyasak et al. 2015).

NO_3 significantly impacts dwarf shrimp, including whiteleg shrimp. Negative effects observed in these shrimp encompass increased mortality, stunted growth, lower feeding rates, lethargy, behavioral stress indicators, bent spines, and various physical deformities (Furtado et al. 2014). Additionally, smaller shrimp exhibit greater sensitivity to NO_3. Similar to NH_3 levels, NO_3 concentrations were found to rise with the age of the whiteleg shrimp during rearing (Fig. 4c). Furthermore, elevated NO_3 levels were detected at the WWTP inlet (Fig. 4d). Similar to the findings of Syah et al. (2017) in their research on super-intensive technology whiteleg shrimp aquaculture, a high NO_3 concentration of 2.3471 mg/L was observed at the WWTP inlet, which decreased to 0.6891 mg/L at the WWTP outlet.

NO_2 in shrimp ponds is a harmful substance that arises from N that has only been partially oxidized. High levels of NO_2 can occur due to overfeeding shrimp, dense sediment

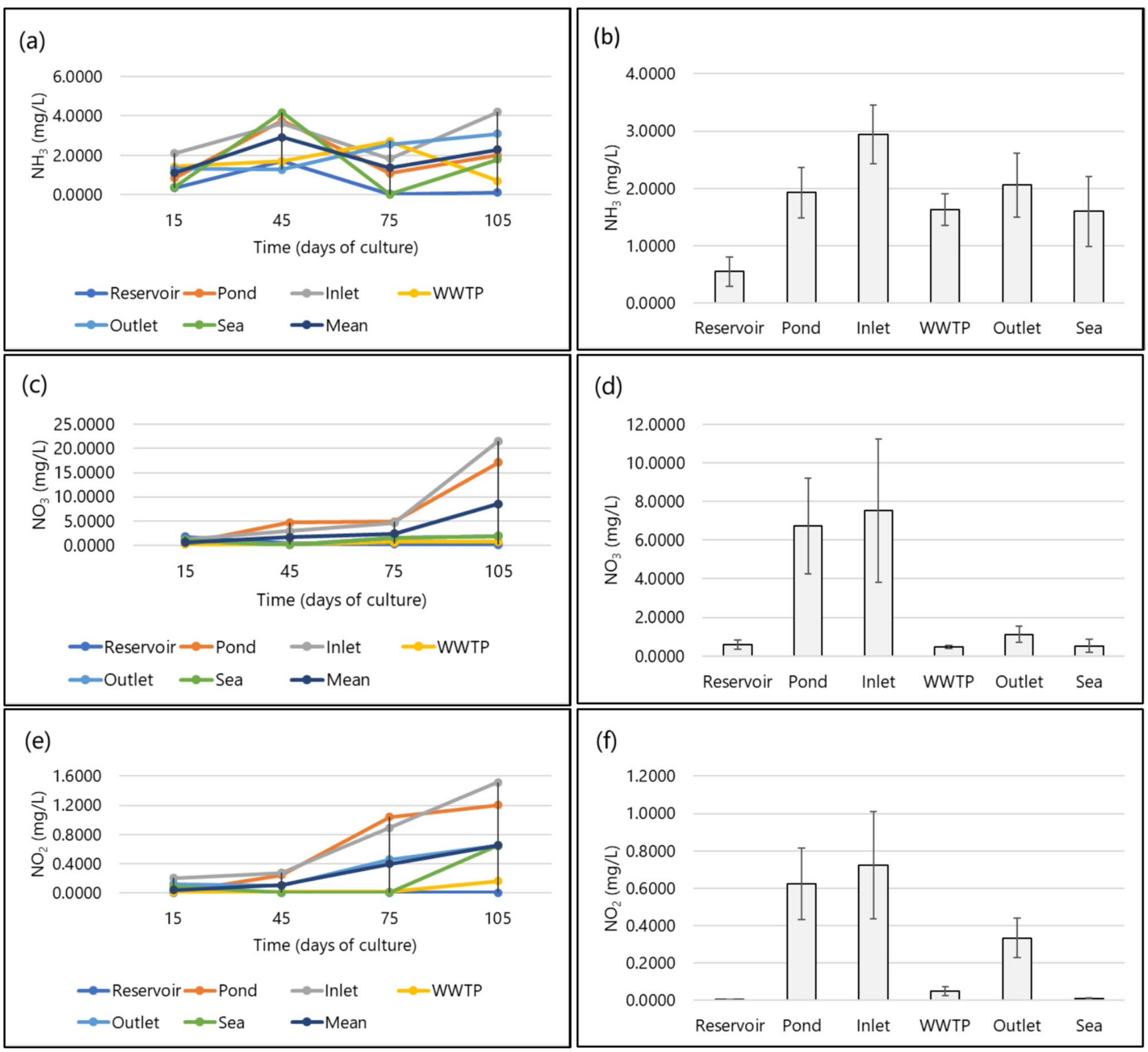

Fig. 4 N compounds of wastewater in different times (left) and locations (right) in intensive technology whiteleg shrimp brackishwater pond aquaculture (**a**, **c**, **e** $n = 2$; **b**, **d**, **f** $n = 8$, average ± standard error)

accumulation, inadequate water circulation, and other factors that disrupt the N cycle (Burford et al. 2002). The presence of NO_2 can lead to various negative outcomes, such as stunted growth and development or even death of shrimp. In comparison to NO_3, NO_2 levels are lower in the wastewater. Figure 4c, d, e, and f illustrate that NO_3 concentrations exceed those of NO_2 at the same time and place. Both NO_3 and NO_2 levels increase as whiteleg shrimp grow older, with the highest concentrations found at the WWTP inlet. Nonetheless, the toxicity of NO_2 to whiteleg shrimp is quite significant.

In general, P is not harmful to humans, animals, or fish/shrimp. However, when P levels are high and combined with N, it can lead to rapid algae growth in water. While P is less toxic than NH_3 or NO_2, the indirect effects of eutrophication can be detrimental to aquatic life (Epifanio and Srna 1975; Mustafa et al. 2020, 2024a). Additionally, as whiteleg shrimp grow older in ponds, PO_4 concentrations tend to rise (Fig. 5a). The highest PO_4 levels have been observed at the WWTP inlet. Syah et al. (2017) have previously reported that in their research on super-intensive technology whiteleg shrimp aquaculture, a high PO_4 concentration of 9.1900 mg/L was observed at the WWTP inlet, which decreased to 0.4448 mg/L at the WWTP outlet. In Bulukumba Regency, intensive whiteleg shrimp aquaculture has been reported to produce a total of 7.67 tons TP/cycle. The application of commercial feed, along with excreta from shrimp and organic fertilizers, contributes to the accumulation of organic P in brackishwater ponds (Bai et al. 2023).

TOM is a water quality indicator in shrimp aquaculture that measures OM from uneaten feed, waste, and metabolic by-products. The acceptable standard for TOM in shrimp aquaculture is less than 90 mg/L. As shown in Fig. 5c, TOM concentration tends to rise with the age of whiteleg shrimp in brackishwater ponds. Additionally, the highest TOM levels were recorded at the WWTP inlet (Fig. 5d). The concentration of TOM, which reached 94.9580 mg/L, was also observed at the WWTP inlet in the super-intensive technology whiteleg shrimp aquaculture (Syah et al. 2017). Elevated TOM levels can result from plankton die-off and excessive feeding. An increase in leftover feed is reflected in the higher TOM levels suspended in the water or settled at the pond bottom (Boyd 2003). The presence of dirty foam on the pond surface also indicates elevated TOM levels. High TOM concentrations and their effects on water quality can influence the amount of feed consumed by the shrimp.

High concentrations of TOM lead to a decrease in DO levels. When TOM is elevated, more OM are available for microorganisms at the pond bottom, resulting in increased BOD_5 and reduced DO concentrations. As whiteleg shrimp age, there is a tendency for BOD_5 to rise (see Fig. 5e). Notably, BOD_5 concentrations drop significantly after treatment in the WWTP. This reduction is likely due to beneficial microorganisms present in the WWTP that help lower BOD_5 levels in the wastewater. A decrease in BOD_5 suggests that most OM in the wastewater is biodegradable. BOD_5 serves as an empirical measure that approximates the biological processes occurring in water. It represents the amount of oxygen required by aerobic bacteria to decompose OM. Most OM dissolve in water, while others remain suspended. BOD_5 is one of the most commonly used metrics for wastewater testing (Kwak et al. 2013).

TOM concentration increases with the increasing age of shrimp aquaculture. A low DO concentration is caused by the decomposition of OM by bacteria, which requires it, causing the bottom of the pond to be in anaerobic conditions. The difference between DO and BOD_5 is that DO is the amount of oxygen dissolved in water, while BOD_5 is the oxygen requirement by organisms for the biodegradation process. Therefore, when the BOD_5 concentration is high, the DO concentration decreases (Islam et al. 2013, 2017). High BOD_5 indicates a high amount of organic waste in the pond. The combined effect of high TOM at the bottom and lack of DO causes the formation of H_2S. H_2S is the by-product of sulfate-digesting bacteria from OM in anaerobic conditions, usually at the pond bottom or mud. H_2S can inhibit shrimp from absorbing oxygen. However, in this study, H_2S measurements were not carried out in brackishwater ponds, but the presence of H_2S can be identified by its smell, especially in the WWTP inlet, WWTP, and WWTP outlet.

TSS and TOM are key indicators used to assess pollution levels (Butler and Ford 2017). Elevated TSS negatively impacts water quality and can lead to gill blockage, resulting in hypoxia that affects shrimp growth (Chang et al. 2022). Increased TSS contributes to higher turbidity, reduces light penetration, and diminishes brightness in the water (Bilotta and Brazier 2008). Throughout the study, the highest TSS levels were recorded at the end, specifically when whiteleg shrimp were raised for 105 DOC. The peak TSS concentration was also observed at the WWTP inlet (Fig. 5g and h). The findings of this study supported the earlier findings by Teichert-Coddington et al. (1999), Wong and Piedrahita (2000), and Jackson et al. (2003), which showed that sedimentation effectively reduced TSS in shrimp aquaculture wastewater. The higher concentration of TSS, which reached 1715 mg/L, was also observed at the WWTP inlet in the super-intensive technology whiteleg shrimp aquaculture (Syah et al. 2017). In laboratory-scale sedimentation and filtration at the WWTP for whiteleg shrimp aquaculture, 5.6% of the TSS in the wastewater can be eliminated (Ramos et al. 2009). After 6 h of sedimentation in a WWTP, the wastewater from whiteleg shrimp and blue shrimp can reduce TSS by 88% (Teichert-Coddington et al. 1999). Typically, WWTP processes like settling and flotation are meant to remove solids but are ineffective against dissolved solids.

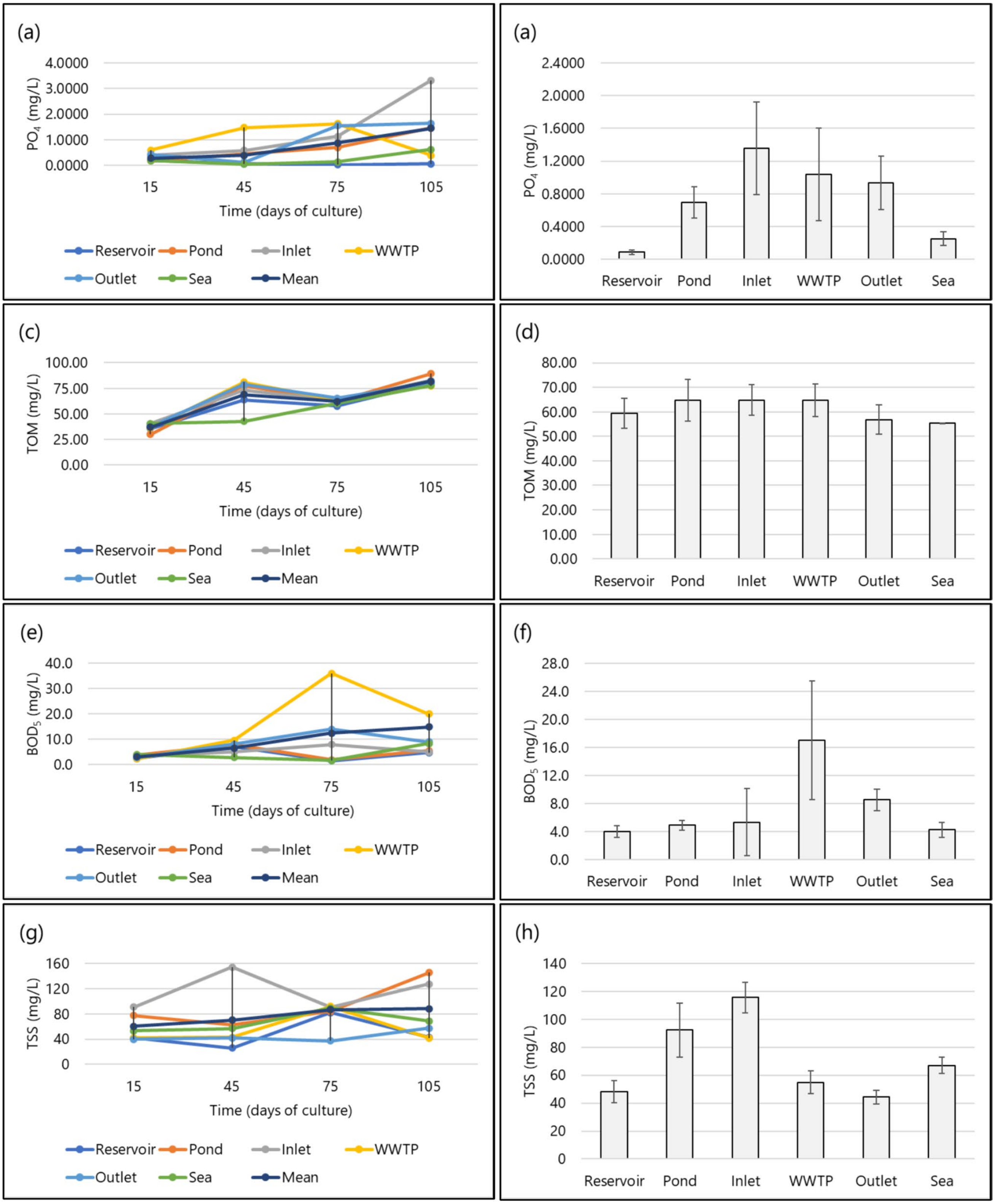

Fig. 5 PO_4, TOM, BOD_5, and TSS concentrations of wastewater at different times (left) and locations (right) in intensive technology whiteleg shrimp brackishwater pond aquaculture (**a**, **c**, **e** $n = 2$; **b**, **d**, **f**, **h** $n = 8$, average ± standard error)

One significant source of TSS in the WWTP is the erosion of the WWTP dike soil.

Overall, the highest levels of toxic compounds in wastewater from intensive whiteleg shrimp aquaculture were observed at the WWTP inlet and when the shrimp were 75 and 105 DOC. The wastewater accumulates at the WWTP inlet prior to treatment and peaks at these shrimp ages. Additionally, the increased concentration of toxic compounds toward the end of the shrimp aquaculture cycle is partly due to partial harvests starting from 60 DOC, leading to a greater volume of water being discharged. In contrast, relatively low concentrations of toxic compounds are found in the sea receiving this wastewater, as it has been treated by the WWTP and undergoes dilution in the seawater.

Performance of wastewater treatment plant

Shrimp aquaculture is closely linked to the surrounding environment and ecosystem. Intensive production of whiteleg shrimp can impact the water quality around brackishwater ponds. If not properly managed, the wastewater from these brackishwater ponds can pollute and degrade the environment. While shrimp brackishwater pond residues are less harmful than industrial waste, they can accumulate in large amounts and negatively affect the environment (Ferreira and Lacerda 2016; Ramos e Silva et al. 2017). The discharge of wastewater from shrimp brackishwater ponds can alter the physical, chemical, and biological conditions of the surrounding aquatic ecosystems (Khalil et al. 2010).

Table 3 presents the wastewater quality at both the WWTP inlet and outlet. It can be observed from Table 3 that there is a noticeable difference in wastewater quality before and after treatment by the WWTP. The *t*-test results indicate that significant differences ($p < 0.1$) were observed for specific variables, namely NO_3, BOD_5, and TSS, between the wastewater before and after passing through the WWTP. This indicates that the WWTP effectively decreases the levels of NO_3 ($p = 0.095$) and TSS ($p = 0.000$), while conversely, it significantly increases the BOD_5 content ($p = 0.080$) from the WWTP inlet to the WWTP outlet. The WWTP, utilizing a sedimentation pond, works by precipitating solid particles in the water. NO_3, being a dissolved ion, is not directly precipitated, but the removal of OM or other particles can lower the amount of OM that could be converted into NO_3 (Song et al. 2013). The sedimentation process separates dissolved and suspended OM in the water. Dissolved OM can be broken down into NO_3 through bacterial decomposition (nitrification), so by reducing the OM concentration, the nitrification process is also diminished (Hooper and DiSpirito 2013). Consequently, reducing OM

Table 3 The average value and standard deviation of each wastewater quality variable ($n = 8$) in the intensive technology whiteleg shrimp brackishwater pond aquaculture, as well as standard values for marine organisms, water sources for whiteleg shrimp aquaculture, and shrimp brackishwater pond aquaculture wastewater

Variables	Value*			Standard value		
	WWTP inlet	WWTP outlet	Significance	Marine organisms**	Water source for whiteleg shrimp***	Shrimp brackishwater pond aquaculture wastewater****
pH	$8.00^a \pm 0.27$	$8.14^a \pm 0.28$	0.317	7.0–8.5	7.5–8.5	6.0–9/0
DO (mg/L)	$4.76^a \pm 1.95$	$3.92^a \pm 1.72$	0.373	> 5	> 4	nd
NH_3 (mg/L)	$2.9394^a \pm 1.4495$	$2.0585^a \pm 1.5787$	0.264	< 0.3	< 0.1	< 0.1
NO_3 (mg/L)	$7.5255^b \pm 10.5468$	$1.2316^a \pm 1.0702$	0.095	< 0.008	< 0.05	< 75
NO_2 (mg/L)	$0.7222^a \pm 0.8105$	$0.3333^a \pm 0.2970$	0.223	nd	< 1.0	< 2.5
PO_4 (mg/L)	$1.3576^a \pm 1.6060$	$0.9348^a \pm 0.9198$	0.529	0.015	0.1–5.0	< 0.1
TOM (mg/L)	$64.7587^a \pm 17.6914$	$56.8388^a \pm 16.9881$	0.377	nd	< 90	nd
BOD_5 (mg/L)	$5.3125^a \pm 1.9504$	$8.4875^b \pm 4.3436$	0.080	20	nd	< 45
TSS (mg/L)	$115.5000^b \pm 31.2318$	$44.2500^a \pm 14.3701$	0.000	Coral: < 20 Mangrove: < 80 Seagrass: < 20	nd	≤ 200

Remarks: nd: no data.

*The same superscript letters indicate statistically not significant differences ($p > 0.05$).

**SME (2004)

***MMAF (2016a).

****Government of Bangka Belitung Islands Provincial (2019).

can decrease the potential for NO_3 formation. In sedimentation pond with an anaerobic zone (low oxygen conditions), the denitrification process can occur. Under anaerobic conditions, denitrifying bacteria convert NO_3 into N_2, which is then released into the atmosphere, thus lowering NO_3 levels in the brackishwater pond water (Rajta et al. 2019). Bacteria that contribute to higher BOD_5 levels in WWTP is typically anaerobic organic-degrading, and hydrolytic microorganisms (Ezeh et al. 2024). Anaerobic decomposers such as *Clostridium* sp. and *Bacteroides* sp. break down complex substances like proteins and carbohydrates into simpler compounds such as organic acids, alcohols, and gases (Liberato et al. 2019). These fermentation by-products are more readily oxidized, leading to an increase in BOD_5. Meanwhile, hydrolytic bacteria such as *Bacillus* sp. and *Pseudomonas* sp. secrete enzymes that degrade complex OM into simpler molecules (Ajuna et al. 2023). Although this process facilitates further treatment, it can temporarily elevate BOD_5 levels.

The sedimentation process in the WWTP helps reduce TSS by allowing water, which contains solid particles like food waste, shrimp feces, and other organic materials, to flow slowly through the sedimentation pond. As the water moves more slowly, heavier particles settle at the bottom due to gravity. Additionally, smaller solid particles can be captured by microorganisms present in the sedimentation tank, which break down OM, further lowering TSS (Lasaki et al. 2023).

While the sedimentation process effectively removes solid particles from wastewater, some finer or dissolved organic materials may not fully settle and remain in the wastewater. These residual particles provide a source of OM for microorganisms to degrade, which increases oxygen consumption during the decomposition process, thus raising BOD_5 (Nguyen et al. 2022). Due to the relatively short 18 h residence time of wastewater in the WWTP, there is limited contact between the wastewater and microorganisms, which means the decomposition process may take longer once the water exits the sedimentation pond. Consequently, oxygen consumption remains elevated. The analysis of the WWTP RE reveals that the WWTP is effective in reducing TSS concentration (RE = 60.05%) and quite efficient in reducing NO_3 (RE = 58.71%), NO_2 (RE = 51.48%), PO_4 (RE = 49.85%), and BOD_5 (RE = 41.15%) (Table 4). In comparison, a WWTP used in a super-intensive technology whiteleg shrimp aquaculture showed significantly higher RE, with values of 99.4% for TSS (very efficient), 70.6% for NO_3 (efficient), 91.6% for NO_2 (very efficient), 95.2% for PO_4 (very efficient), and 64.1% for BOD_5 (efficient) (Syah et al. 2017). This suggests that the WWTP in the super-intensive technology whiteleg shrimp aquaculture is more efficient at reducing wastewater pollutants. This higher efficiency is attributed to the inclusion of sedimentation, aeration, and equalization ponds in the super-intensive technology, as reported by Syah et al. (2017), whereas the WWTP in this study only includes sedimentation ponds. However, when compared to the study by Mangarengi et al. (2019), which also used a sedimentation pond-only system, the RE for TSS (63.4%, efficient) and PO_4 (59.21%, quite efficient) is similar to the results obtained in this study. RE for BOD_5 in WWTP have been reported in the literature to range from 50 to 95%.

Table 4 Removal efficiency of WWTP and level of WWTP removal efficiency in the intensive technology whiteleg shrimp brackishwater pond aquaculture

Variables	RE of WWTP (%)	Level of WWTP RE
pH	3.81	Inefficient
DO (mg/L)	24.23	Less efficient
NH_3 (mg/L)	15.07	Inefficient
NO_3 (mg/L)	58.71	Quite efficient
NO_2 (mg/L)	51.48	Quite efficient
PO_4 (mg/L)	49.85	Quite efficient
TOM (mg/L)	12.63	Inefficient
BOD_5 (mg/L)	41.15	Quite efficient
TSS (mg/L)	60.05	Efficient

From Table 4, it is evident that the WWTP used for intensive whiteleg shrimp brackishwater ponds is only considered inefficient in reducing TOM, while it is increasing BOD_5. However, both variables meet the standards for intensive whiteleg shrimp aquaculture (Table 3). This indicates that a high RE value is not necessary, as the system is sufficient to lower the concentrations to the required levels. The WWTP is also regarded as fairly efficient in reducing NH_3 and PO_4 concentrations (Table 4), but these two variables do not meet the standards for intensive whiteleg shrimp aquaculture (Table 3).

These two data analysis results indicate that WWTP can improve wastewater quality for certain variables, but their capacity and capabilities are inadequate for handling wastewater from intensive whiteleg shrimp aquaculture. As noted earlier (Table 2), the WWTP area constitutes only 9.51% of the total pond area, and the wastewater retention time is relatively short, at just 18 h.

The WWTP system used for intensive whiteleg shrimp aquaculture in Bulukumba Regency consists primarily of sedimentation ponds or constructed wetlands with a hydrological design focused on water surface flow. Sedimentation ponds work by separating suspended particles from wastewater through gravity settling, without the need for chemical additives. This makes the WWTP effective in addressing the physical property of TSS. Specifically, sedimentation ponds play a crucial role in reducing the TSS concentration in wastewater, decreasing it from 1715 mg/L at the WWTP inlet to 437 mg/L at the WWTP outlet, achieving a removal RE of 74.5% (Syah et al. 2017), which is considered efficient. According to Abuhasel et al. (2021), sedimentation ponds can reduce TSS by up to 60%. A WWTP, mainly consisting of free water surface and subsurface flow constructed wetland cells effectively removed TSS (55–66%) from the recirculating water under high hydraulic loading rates (1.57–1.95 m/day) (Lin et al. 2005). However, the WWTP in Bulukumba Regency is less efficient in treating the chemical properties of the wastewater due to limited processes like adsorption, microbial nitrification, and assimilation. The key nutrient removal processes in these systems include adsorption (the co-precipitation of inorganic P and metals), microbial nitrification (under aerobic conditions), microbial denitrification (under anaerobic conditions), anaerobic NH_4 oxidation (anammox), and assimilation into plant biomass (Vymazal 2007, 2008).

Table 3 shows that the WWTP in the intensive whiteleg shrimp aquaculture can reduce toxic compounds such as NH_3 and NO_3, but their concentrations remain above the recommended threshold for whiteleg shrimp. This is further confirmed by the CI values, which are below 1.00 for NH_3, NO_3, and PO_4, indicating that the WWTP performance does not meet the required standards for significantly reducing these substances (as indicated by the red color in Table 5). However, the WWTP is effective in significantly lowering the concentrations of NO_2, TOM, and TSS, while also raising the pH of the wastewater, and is thus classified as compliant (with CI < 1.00, green color) in these aspects (Table 5).

NH_3 is a key limiting factor in crustacean aquaculture and a major pollutant in aquatic environments, making it an important variable to monitor for assessing water quality (Chang et al. 2015; Xiao et al. 2019). It impacts crucial

Table 5 The compliance index of each variable of wastewater from intensive technology whiteleg shrimp brackishwater pond aquaculture in different of times and locations

Time (DOC)	Locations	pH	DO	NH_3	NO_3	NO_2	PO_4	TOM	BOD_5	TSS
15	Reservoir	0.90	0.99	0.94	33.24	0.01	0.83	0.89	0.12	0.21
	Pond	0.86	0.72	2.82	6.54	0.01	1.73	0.99	0.19	0.39
	Inlet	0.92	0.70	7.00	22.42	0.21	3.93	0.92	0.16	0.45
	WWTP	0.90	0.71	4.74	4.33	0.01	5.89	0.86	0.12	0.21
	Outlet	0.92	0.73	4.40	20.66	0.12	4.27	0.78	0.14	0.20
	Sea	0.89	1.49	1.29	3.65	0.01	1.91	0.87	0.20	0.27
45	Reservoir	0.88	0.94	5.66	6.92	0.01	0.59	0.40	0.36	0.13
	Pond	0.85	0.89	12.53	93.33	0.24	4.44	0.33	0.40	0.31
	Inlet	0.89	0.63	12.11	58.00	0.28	5.83	0.45	0.25	0.77
	WWTP	0.89	0.60	5.66	5.28	0.01	14.78	0.41	0.48	0.22
	Outlet	0.85	0.86	4.25	1.76	0.10	1.24	0.36	0.41	0.21
	Sea	0.93	1.64	13.93	2.00	0.01	0.48	0.45	0.14	0.29
75	Reservoir	0.78	0.69	0.11	4.33	0.01	0.13	0.71	0.08	0.41
	Pond	0.88	0.72	3.65	95.93	1.04	6.96	0.86	0.10	0.42
	Inlet	0.85	2.48	6.07	91.24	0.89	11.26	0.81	0.40	0.45
	WWTP	0.86	2.36	9.01	12.32	0.02	16.32	0.90	0.98	0.46
	Outlet	0.93	3.07	8.53	29.77	0.46	15.55	0.76	0.70	0.19
	Sea	0.95	1.77	0.09	6.84	0.03	1.38	0.48	0.09	0.45
105	Reservoir	0.94	0.64	0.04	3.32	0.01	0.60	0.64	0.24	0.22
	Pond	0.95	0.70	6.69	94.63	1.20	14.62	0.69	0.28	0.73
	Inlet	0.90	0.79	14.01	99.75	1.51	33.28	0.70	0.25	0.64
	WWTP	0.93	0.78	2.33	14.91	0.16	3.90	0.71	0.99	0.21
	Outlet	0.92	0.94	10.27	37.35	0.65	16.33	0.62	0.45	0.29
	Sea	0.96	0.60	5.95	29.29	0.01	6.17	0.67	0.42	0.34

Remarks:

: CI < 1.0, Compliance

: CI ≥ 1.0, Non-compliance

physiological and pathological processes in organisms, including crustaceans (Cui et al. 2017; Zhao et al. 2020). When NH_3 levels surpass established quality standards, it can become toxic to the aquatic organisms (Tanjung et al. 2019).

NO_3 is a less toxic form of N compared to NO_2 and NH_3, but it can still be harmful to shrimp at elevated concentrations. Prolonged exposure to high levels of NO_3 has been linked to shorter antennae, gill deformities, and blisters in the hepatopancreas of shrimp (Walker and Winton 2010; Furtado et al. 2014). According to Walker and Winton (2010) and Lee et al. (2022), the shortening of antennae and gill deformities are commonly seen as early signs of health decline in shrimp.

The WWTP for intensive whiteleg shrimp aquaculture reduces the DO concentration at its WWTP outlet, causing it to fall below the recommended level for shrimp aquaculture. This drop is believed to result from aerobic bacteria consuming DO to break down OM in the wastewater. The various stages of the WWTP lead to a gradual decrease in DO, initially facilitating NH_3 and OM oxidation, followed by the reduction of NO_2 and NO_3. This differs from WWTP used in super-intensive whiteleg shrimp aquaculture, which features an aeration pond with paddle wheels to increase DO levels (Syah et al. 2017).

Changes in water quality characteristics can serve as immediate indicators of deteriorating water quality, especially in coastal regions. The concept of "water quality status" refers to the condition of the water, indicating whether contamination has occurred within a specific timeframe. Various methods have been developed to assess these changes, including those used in Indonesia. Water quality indicators in Indonesia are based on established standards from various sources. The Storet analysis was applied to assess the water quality status across different locations and timeframes in areas of intensive whiteleg shrimp aquaculture (see Table 6).

The analysis results reveal that the total scores for the grow-out pond, the WWTP inlet, the WWTP outlet, and the sea are −20, between −20 and −36, −20, and between −20 and −22, respectively (see Table 6). The wastewater quality at the grow-out pond, WWTP outlet, and sea at 15, 45, 75, and 105 DOC falls under class C, which is categorized as moderate or moderately polluted. In contrast, the wastewater quality at the WWTP inlet at 75 and 105 DOC is classified as class D, indicating poor or heavily polluted water. These findings indicate that no location in the intensive technology whiteleg shrimp aquaculture falls within class A (excellent) or class B (good or slightly polluted), which meet the standard quality criteria. Mustafa et al. (2024b) previously reported a shift in wastewater quality status in Arungkeke District, Je'neponto Regency, South Sulawesi Province, from class B (good) before shrimp aquaculture to class C (moderate) after intensive whiteleg shrimp aquaculture. The only wastewater quality variables that exceeded the recommended thresholds for marine organisms were DO, NH_3, NO_3, and PO_4 concentrations (CI value > 1.00). Other variables such as pH, NO_2, TOM, BOD_5, and TSS (CI value < 1.00) were within acceptable limits for marine organisms. The primary factor contributing to the degraded wastewater quality was NO_3, which was likely caused by feed residues and shrimp waste. In intensive technology shrimp aquaculture, N plays a crucial role in the balance between nutrients and toxicity (Thakur and Lin 2003; Burford and Lorenzen 2004). NO_3 has also been identified as the main cause of deteriorating water quality in Je'neponto Regency, South Sulawesi Province (Mustafa et al. 2024b). Additionally, Purnomo et al. (2022) found that NO_3 and PO_4 levels exceeded water quality thresholds in the Karimunjawa-Jepara-Muria Biosphere Reserve, Central Java Province due to intensive whiteleg shrimp aquaculture. Therefore, effective management and monitoring of water quality are vital for maintaining healthy conditions in shrimp aquaculture operations.

Table 6 Total score and wastewater quality status in different locations and times in intensive technology whiteleg shrimp brackishwater pond aquaculture

Locations	Total score and class			
	15 DOC	45 DOC	75 DOC	105 DOC
Pond	− 20 (class C)	− 20 (class C)	− 20 (class C)	− 20 (class C)
Inlet	− 20 (class C)	− 20 (class C)	− 32 (class D)	− 36 (class D)
WWTP	− 20 (class C)	− 20 (class C)	− 32 (class D)	− 36 (class D)
Outlet	− 20 (class C)	− 20 (class C)	− 20 (class C)	− 20 (class C)
Sea	− 20 (class C)	− 20 (class C)	− 22 (class C)	− 22 (class C)

Remark:

Class C = moderate or moderately polluted.

Class D = poor or heavily polluted.

In addition to physicochemical methods like sedimentation, N removal in WWTP using constructed wetlands is achieved through processes such as ammonification, nitrification, denitrification, and plant uptake, including by aquatic plants (Lee et al. 2009). Ammonification refers to the biological conversion of organic N into NH_3. N-containing pollutants are rapidly degraded in both aerobic and anaerobic zones, releasing NH_3. The main mechanisms for NH_3 removal in WWTP are nitrification and denitrification. In constructed wetlands, NH_3 can also be reduced through processes like adsorption, plant uptake, and volatilization (Vymazal 2007). However, these additional processes contribute only minimally to NH_3 removal compared to nitrification and denitrification (Ruiz-Filippi et al. 2006; Lee et al. 2009; Strong et al. 2011).

The decomposition process in WWTP is thought to convert the majority of organic N into NH_3 (Mayo and Mutamba 2004). In constructed wetlands, the primary mechanism for NH_3 removal is biological nitrification, which is performed by nitrifying bacteria such as *Nitrosomonas* sp., *Nitropira* sp., *Nitrosococcus* sp., and *Nitrobacter* sp., followed by denitrification (Gersberg et al. 1985; Ying et al. 2016). Biological N removal involves two key stages: nitrification and denitrification. Nitrification is a chemo-lithoautotrophic process that oxidizes NH_3 to NO_3 under aerobic conditions. This occurs in two steps: NH_3 is first oxidized to NO_2, and then NO_2 is oxidized to NO_3 (Gutiérrez et al. 2024). *Nitrosomonas* sp. is primarily responsible for NH_3 oxidation, while *Nitrobacter* sp. handles NO_2 oxidation. However, the acid by-products of nitrification can significantly lower the pH. pH is a critical factor in nitrification, as the process slows considerably when the pH drops below 7.0 (Ahn 2006; Hossain et al. 2022). Therefore, it is important to add chemicals such as lime to maintain an optimal pH during nitrification.

Biological denitrification processes use NO_3 as the final electron acceptor in low-oxygen environments. This process plays a crucial role in controlling N compounds, including NO_3, by converting it into N gas (N_2) (Morrissey and Franklin 2015). Denitrification is the primary pathway for removing N from aquatic systems (Laverman et al. 2010). It occurs only in anoxic zones, as the presence of DO inhibits the enzymes required for the process (Tchobanoglous and Burton 1991). Typically, denitrification accounts for 60–95% of RE for N, while plants and algae assimilate just 1–34% of N (Omar et al. 2024). Under anoxic conditions, heterotrophic microorganisms use oxidized forms of N (NO_2 and NO_3) as electron acceptors and organic C as electron donors (Tchobanoglous and Burton 1991). Additionally, N can be managed through NH_3 and NO_3 absorption by phytoplankton, as well as through strategies like proper feeding, water changes, recirculation systems, and bioremediation using heterotrophic bacteria via probiotic administration. Numerous studies and direct evidence in the field demonstrate the advantages of using probiotics, such as decreasing the levels of NH_3, NO_3, NO_2, H_2S, organic waste (from leftover feed, feces, and other OM), and the risk of disease. In Bulukumba Regency, intensive whiteleg shrimp aquaculture ponds use probiotics in the grow-out ponds.

The study evaluating the RE of WWTP for intensive whiteleg shrimp aquaculture in Bulukumba Regency indicates that the nitrification and denitrification processes in wastewater help remove NH_3, which, along with P, contributes to eutrophication. Therefore, it is crucial to consider all relevant conditions to optimize these processes. One key factor to monitor effective nitrification is the pH of wastewater. The optimum pH is 7.5 (Gerardi 2002), as this pH level allows N to be most accessible to the microorganisms involved in nitrification. If the pH deviates from this range, the reaction rate may significantly decrease, and if it drops below 5.5, nitrification can be entirely inhibited (Jiménez et al. 2011). Maintaining a pH above 7.5 is vital because the oxidation of NH_3 to NO_2 consumes alkalinity (Jiménez et al. 2011).

Conversely, if the pH level is too high, the conversion of NO_2 to NO_3 through oxidation becomes less efficient. Temperature also plays a crucial role in nitrification. The optimum temperature range is between 28 and 32 °C. Since nitrification relies on microorganisms, the temperature of the wastewater should not drop below 4 °C or exceed 45 °C (Le et al. 2019). Outside this range, the reaction rate significantly decreases as the microorganisms slow down. Another critical factor is the DO concentration in the water. As nitrifying microorganisms are aerobic and require oxygen, the DO concentration should be around 3 mg/L for optimum nitrification rates (Meng et al. 2008). If the DO falls below 1.5 mg/L, nitrification slows considerably and is completely inhibited at 0.5 mg/L. Additionally, microorganisms are sensitive to various chemical pollutants that may be present in wastewater, such as solvents, amines, phenols, ethers, and metals (Sinha and Annachhatre 2006). These contaminants can not only reduce the efficiency of the nitrification process but can also kill the microorganisms if their concentration is too high. Therefore, it is important to monitor and remove any toxic substances that could harm microorganisms during wastewater to be treated.

Denitrification, in contrast to nitrification, is largely unaffected by pH. While the ideal pH range for denitrification is between 7.0 and 8.0, the reaction rate only experiences a slight decrease if the pH falls outside this range, since bicarbonate (an alkaline substance) is produced during the process (Peyton et al. 2002). Similar to nitrification, denitrification relies on microorganisms to convert NO_3 into N_2. These microorganisms thrive within a temperature range of 28 to 32 °C, with activity significantly decreasing above 45 °C or below 4 °C (Alawi et al. 2009). DO also plays a crucial role in denitrification. As the microorganisms involved in this process are anaerobic (requiring an oxygen-free environment), the presence of oxygen can be detrimental, slowing or even halting denitrification. For instance, a DO concentration of just 0.2 mg/L can inhibit the process (Raboni et al. 2020). However, denitrification and nitrification can occur in a hybrid system that includes both aerobic and anaerobic conditions in the same environment.

Numerous studies indicate that RE of PO_4, including the removal of PO_4 in constructed wetlands, ranges from 15 to 70%, with significant variations depending on factors like substrate type and temperature (Cheng et al. 2018; Song et al. 2021). In the WWTP, RE of P has been reported to range between 30 and 95% (Bunce et al. 2018). In this study, the RE of PO_4 in the WWTP was 49.85% (Table 4). The mechanisms behind P removal in constructed wetland substrates remain poorly understood, with limited study on this topic. It is generally believed that P removal in constructed wetlands involves a combination of physical, chemical, and biological processes, which can be categorized into three main components: (a) plant uptake and assimilation, (b) absorption and excessive accumulation of P by P-accumulating bacteria, and (c) interception, filtration, and adsorption by the substrates (Gao and Zhang 2022). However, studies on the specific contributions of each process and how P dynamics unfold in constructed wetlands are still sparse.

Another WWTP system is the Recirculating Aquaculture System (RAS), which purifies wastewater by removing toxic pollutants and recycling the treated water. It requires only 10% of the total freshwater volume for large-scale fish production, making it more sustainable than the traditional system (Tom et al. 2021). However, the RAS system has drawbacks, including lower hydraulic loads and NO_3 accumulation, which can lead to eutrophication and fish toxicity (Jusoh et al. 2020). Additionally, the high energy demands for oxygen supply and toxicity removal in aquaculture systems make it economically impractical (Tom et al. 2021). To address the limitations of the RAS system, the introduction of artificial wetlands for WWTP is an innovative solution. As seen in this study, where the WWTP is designed with wetland construction, artificial wetlands are highly effective at treating wastewater containing N compounds (Sindilariu et al. 2007). However, in large-scale systems, while wetlands can efficiently remove NH_4 and NO_2, they often do not effectively address NO_3 and PO_4 removal, and in some cases, the removal of these substances may be hindered (Tom et al. 2021). In this study, the WWTP demonstrates quite efficiency in removing NO_3 and PO_4 from the water, yet the levels still surpass the acceptable threshold for whiteleg shrimp aquaculture. This means that long retention times and a significant land area are required. Aquaponics is another system of aquaculture wastewater treatment, offering a solution to the limitations of artificial wetlands in the RAS system. In this system, plants are selectively used to both supply oxygen to waste and absorb nutrients from it (Webb et al. 2012).

An alternative for wastewater treatment plant development

The shift from traditional to intensive and super-intensive technologies whiteleg shrimp aquaculture could lead to severe environmental pollution (Mustafa et al. 2022, 2023). Unregulated organic waste from shrimp brackishwater ponds can result in environmental degradation and unnecessary financial costs (Chaikaew et al. 2019; Dauda et al. 2019). The high concentration of OM in shrimp effluent poses significant risks to small inland waterways, which typically have limited ability to absorb these pollutants (Jiang et al. 2019). This can cause algae blooms and hypoxia in nutrient-laden waters (Ballah et al. 2019), weakening the immunity of aquatic organisms and leading to mass die-offs. In extreme cases, toxic waste can make the environment uninhabitable for aquatic organisms, particularly benthic species (Nguyen et al. 2019; Manatura and Samaksaman 2021).

The intensive and super-intensive technologies whiteleg shrimp aquaculture also impacts the quality of nearby coastal waters. The solid waste from whiteleg shrimp aquaculture, if not properly treated, contains high concentrations of OC, TN, and TP (Mustafa et al. 2022). For example, a 1000 m^2 pond with a whiteleg shrimp stocking density of 500 ind./m^2 produces 50.12 g of TN/kg of shrimp, 15.73 g of TP/kg of shrimp, and 126.85 g of OC/kg of shrimp (Syah et al. 2014). Feed is the primary source of waste in intensive shrimp aquaculture (Martins et al. 2010; Olusegun et al. 2016), with waste being released into the surrounding aquatic environment as both sediments and suspended particles.

Maintaining good water quality is crucial for productive and sustainable whiteleg shrimp aquaculture, as it supports both the shrimp needs and its natural food sources. To ensure this, regular water changes are necessary during the aquaculture process. However, these water changes result in wastewater discharge, which can potentially harm the environment (Owhonka et al. 2021). Proper management of whiteleg shrimp brackishwater pond wastewater is essential, making the use of a WWTP vital for effective waste management.

Over the past two decades, the use of constructed wetlands for treating brackishwater pond wastewater has evolved into a sophisticated wastewater treatment system. This system has also been adopted in intensive whiteleg shrimp aquaculture in Bulukumba Regency. Constructed wetlands offer several advantages over other brackishwater pond aquaculture wastewater treatment systems, including low maintenance costs, ease of operation, and cost-effectiveness (Abou-Elela et al. 2013). The restoration of wastewater quality in these systems can occur through integrated physical, chemical, and biological processes (Wu et al. 2015), which enhances wastewater quality (Abou-Elela et al. 2013; Bilgin et al. 2014). However, in Bulukumba Regency, where whiteleg shrimp aquaculture covers an area of 16.08 ha, it has been recommended that a constructed wetland WWTP area of 3.22 ha, or 20% of the total pond area, be established (Syah et al. 2017; DGA 2019). This size of WWTP can handle a minimum liquid waste height of 1.0 m, meaning the existing WWTP must be constructed at a greater depth. A constructed wetland of this size will allow for a wastewater residence time more than 2 days. The extended residence time will also reduce the water flow to below 20 m/s, which improves the sedimentation process.

It is recommended that the sedimentation pond be implemented first to decrease OM and TSS, as well as to facilitate the denitrification of NO_3 into N_2. Biological denitrification is a cost-effective and efficient method for reducing NO_3, as it relies on naturally occurring organisms to transform NO_3, making it an environmentally friendly process (Wang et al. 2017; Athirah et al. 2020). Several innovative and sustainable technologies are available to mitigate environmental pollution from shrimp pond activities (Tong et al. 2021). It has been mentioned previously that wastewater that has passed through the WWTP has decreased DO and increased BOD_5 at the WWTP outlet. To address this, it is recommended that the WWTP system be fitted with an aeration pond. This pond, which incorporates an aeration system, is designed to enhance DO levels, reduce BOD_5, and raise pH in the wastewater. It also helps remove CO_2, H_2S, and other dissolved gases. The aeration pond facilitates the oxidation of OM by aerobic bacteria and supports nitrification.

Along with the sedimentation and aeration ponds, it is also recommended to include an equalization pond in the WWTP system. The equalization pond serves as the final storage area for wastewater, where all treated water is collected and stored. One such method involves optimizing the use of natural resources and improving the cultural environment, such as incorporating aquatic plants in or around the WWTP (Mariscal-Lagarda and Páez-Osuna 2014), including in the equalization pond. The use of aquatic plants, including seaweed species like *Kappaphycus alvarezii*, to absorb N compound (NH_3, NO_3, NO_2) and PO_4 from shrimp ponds, is gaining popularity in Asia (Syah et al. 2017; Burford et al. 2020). This seaweed is typically placed after the aeration pond in an equalization pond, where it can efficiently absorb excess N and P. Utilizing biofilter organisms, such as seaweed, is one of the most affordable and simple ways to manage wastewater from intensive whiteleg shrimp aquaculture (Boock et al. 2016). Constructed wetlands with halophytic plants offer the potential for waste-stream treatment combined with production of valuable secondary plant crops (Webb et al. 2012). Syah et al. (2017) also recommended the use of tilapia (*Oreochromis niloticus*) or mujair (*Oreochromis mossambicus*) in equalization pond. In this context, the presence of seaweed or other aquatic plants alongside fish plays a crucial ecological role in enhancing the quality of wastewater from intensive whiteleg shrimp aquaculture. The integration of tilapia and moss (*Enteromorpha* sp.) in a recirculating system alongside whiteleg shrimp helps to absorb the waste load from shrimp aquaculture wastewater (Attasat et al. 2013). Adsorption, a long-term process for P sequestration in constructed wetlands, plays a crucial role in removing P (Vymazal 2009). This approach is considered highly effective, environmentally friendly, and sustainable with no negative side effects. Maintaining water quality is a major concern for the aquaculture industry, as a healthy aquatic environment is vital for both operational success and long-term sustainability. Performance assessment systems, as noted by Quadros et al. (2010) and Mahapatra et al. (2022), are important tools for the cost-effective and sustainable management of WWTP. The proposed WWTP should be efficient, cost-effective, easy to construct, and simple to operate. Monitoring and enforcement of the WWTP standards before discharge into water bodies will help minimize the environmental impact of wastewater.

To evaluate the economic feasibility of expanding the WWTP from 1.53 to 3.22 ha, including the addition of an aeration and equalization ponds, several factors need to be considered. However, this analysis focuses primarily on the key cost components, without specifying the economic value of each one. The primary cost component is the investment cost, which covers planning, design, and construction of the WWTP. Key elements to calculate include land acquisition costs, construction costs (particularly for the aeration and equalization ponds), and additional infrastructure costs, such as piping. Another significant component is operational costs, which are limited to maintenance expenses. Labor, energy, and management costs are not considered in the operational costs, as the WWTP will be constructed wetlands and designed to allow wastewater to flow by gravity. A paddle wheel is all that is needed to boost the DO levels in the aeration pond, while a mud pump is required to assist in draining the sludge from the sedimentation pond. In terms of economic benefits, the expansion will enhance the plant waste processing capacity and ensure compliance with stricter environmental standards (Roy and Kumar 2025). It will also result in more efficient waste treatment, reducing environmental pollution and improving the quality of source water. Consequently, this is expected to lead to more optimum growth of whiteleg shrimp, higher survival rate, longer culture period, improved weight and quality, a lower FCR, and sustainable aquaculture practices.

This results in higher production within the same time frame, with larger sizes boosting market value. Additionally, lower FCR enhance feed efficiency, leading to greater economic gains. Improved efficiency in whiteleg shrimp aquaculture ensures more consistent profits for farmers, helping them thrive in the long run while minimizing the economic instability associated with inefficient aquaculture practices (Chaikaew et al. 2019). Sustainable aquaculture practices also mitigate environmental harm, such as pollution and water quality decline. This creates a more resilient system, better equipped to withstand climate change and other environmental shifts, reducing the risk of long-term financial setbacks for farmers. Overall, if the factors mentioned above can be implemented properly, improving the WWTP can have a very positive impact in terms of economic feasibility, both in terms of direct benefits for farmers and industry, as well as in increasing competitiveness in the global market and the sustainability of whiteleg shrimp aquaculture in Indonesia. The study highlights gaps and opportunities for future investigation, emphasizing the need for interdisciplinary approaches and greater collaboration among stakeholders. Policies based on data and study results will be more effective and targeted. Its findings offer valuable guidance to policymakers, practitioners, and researchers, helping them tackle challenges and seize opportunities in industrial wastewater management.

Conclusions and suggestion

In Bulukumba Regency, Indonesia, intensive whiteleg shrimp aquaculture practices generate wastewater containing 13.13 tons of TN and 7.67 tons of TP/cycle. The WWTP employed consists of constructed wetlands with both surface and subsurface water flow designs. The area of the WWTP covers 9.51% of the total pond area, with a wastewater residence time of 0.76 days. The system is efficient in reducing TSS and is quite efficient in removing NO_3, NO_2, PO_4, and BOD_5. The WWTP significantly reduces concentrations of NO_2, TOM, BOD_5, and TSS, while also increasing the pH of the wastewater, making it compliant (with a compliance index, CI < 1.00). The quality of wastewater at the WWTP inlet is classified as class D (poor or heavily polluted), improving to class C (moderate or moderately polluted) at the WWTP outlet. The wastewater quality remains in class C at 75 and 105 DOC. Overall, the WWTP is successful in enhancing the quality of wastewater from intensive whiteleg shrimp brackishwater pond aquaculture. However, it has shown limited effectiveness in improving the levels of specific pollutants like NH_3, NO_3, and PO_4. To improve the system's efficiency, it is suggested to expand the WWTP area to 3.22 ha, increase the residence time to a minimum of 2 days, and add an aeration and equalization ponds to the system.

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Author contribution Akhmad Mustafa: conceived and designed the study, carried out the study, performed the acquisition of data, data analyses, and interpretation, wrote and reviewed the manuscript, funding acquisition. Rachman Syah: conceived and designed the study, carried out the study, performed the acquisition of data, reviewed the manuscript. Mudian Paena: conceived and designed the study, carried out the study, performed the acquisition of data, reviewed the manuscript. Tarunamulia: conceived and designed the study, carried out the study, performed the acquisition of data, reviewed the manuscript. Wasir Samad: conceived and designed the study, performed the acquisition of data, data analyses, and interpretation. Erna Ratnawati: carried out the study, performed the acquisition of data, project administration. Admi Athirah: carried out the study, performed the acquisition of data, project administration. Ruzkiah Asaf: carried out the study, performed the acquisition of data, project administration. Akmal: carried out the study, performed the acquisition of data, project administration. Kamariah: carried out the study, performed the acquisition of data, project administration. Mohammad Syaichudin: carried out the study, performed the acquisition of data. Hamzah: carried out the study, performed the acquisition of data. Imam Taukhid: carried out the study. All authors discussed the results and contributed to the final manuscript. Major contributors are Akhmad Mustafa, Rachman Syah, Mudian Paena, Tarunamulia, and Wasir Samad while member contributors are Erna Ratnawati, Admi Athirah, Ruzkiah Asaf, Akmal, Kamariah, Zylshal, Mohammad Syaichudin, Hamzah, and Imam Taukhid.

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Declarations

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