



Experimental Study Article

Physical Characteristics of Seawater as Raw Material for Salt Pond Production in the Padelegan Coastal Area, Pamekasan, Madura

Nike I. Nuzula^{1*}, Diah Ayu Setyawati², Wiwit Sri W. Pratiwi¹, Eka Nurrahema Ning Asih¹, Ary Giri D. Kartika¹ and Makhfud Efendy¹

¹Marine Science Department, Universitas Trunojoyo Madura, Indonesia

²PT. Grobest Indomakmur, Indonesia

*nike.nuzula@trunojoyo.ac.id

Abstract: The Padelegan coast of Pamekasan, Madura, is an important source of raw seawater for traditional salt ponds; however, the suitability of this water is strongly affected by spatial variation in physical properties. This study evaluated the physical characteristics of seawater used as salt-pond raw material at 15 stations representing nearshore, estuarine, and offshore waters. Temperature, salinity, brightness, turbidity, and total dissolved solids (TDS) were measured in situ, whereas total suspended solids (TSS), viscosity, density, and specific gravity (SG) were analyzed in the laboratory. Descriptive statistics, Pearson correlation, and spatial visualization were performed in RStudio using R. Salinity ranged from 29.67 to 32.67 ppt, temperature from 27.67 to 31.60 °C, brightness from 0.35 to 0.80 m, turbidity from 0.08 to 64.5 NTU, and density from 1.006147 to 1.008313 g/cm³. Nearshore and estuarine stations generally showed higher turbidity and TSS and lower water transparency, indicating a stronger influence of suspended sediments and land-derived inputs. In contrast, offshore stations showed clearer water and more stable marine characteristics. Brightness was strongly positively correlated with temperature ($r = 0.84$), while salinity and density showed a moderate positive correlation ($r = 0.59$) within the observed dataset. These findings indicate that raw seawater intake for salt ponds in Padelegan should prioritize clearer and more stable water sources, while sediment control is required at land-influenced stations to improve salt-pond productivity and raw-material quality.

Keywords: seawater physical properties; salinity; salt ponds; raw seawater; Padelegan Coast; Madura

1. Introduction

The Padelegan coastal area, located in Pademawu District, Pamekasan Regency, Madura, is one of the important salt-producing areas in East Java. The performance of solar salt ponds depends strongly on the quality of raw seawater entering the evaporation system. In salt production, physical properties such as temperature, salinity, turbidity, transparency, total dissolved solids (TDS), total suspended solids (TSS), density, viscosity, and specific gravity influence evaporation efficiency, brine concentration, sediment load, and the suitability of seawater as raw material [1]-[4]. These physical characteristics are also closely related to

evaporation-based salt concentration processes, salt pond hydrodynamics, and brine evolution during solar salt production [5]-[7].

Seawater physical properties vary spatially and temporally because of tides, river discharge, rainfall, evaporation, coastal morphology, and human activities [8]-[10]. Average open-ocean salinity is approximately 35 ppt, or about 35 g of dissolved salt per kilogram of seawater, not one kilogram of salt per liter of seawater [11]. Coastal salinity may be lower or higher than this value depending on freshwater dilution, evaporation, residence time, and mixing. Therefore, localized measurements are required before seawater is used as salt-pond feedwater.

Previous studies have described seawater

properties in general oceanographic settings and in large-scale coastal monitoring programs. However, fewer studies have examined the small-scale spatial variability of raw seawater around active salt-pond systems. This gap is important because salt ponds operate at shallow depths, have high evaporation rates, and are frequently connected to estuaries, drainage channels, fishing areas, settlements, and coastal activities. These local factors can alter the physical properties of incoming seawater and may reduce the efficiency and quality of salt production.

The novelty of this study lies in its salt-pond-oriented inventory of seawater physical properties in the Padelegan coastal system. Rather than treating the coast as a uniform water body, this study compares stations representing land-influenced, estuarine, nearshore, and offshore conditions and evaluates how their physical characteristics relate to salt-pond raw-material suitability. The study also integrates field measurements, laboratory analyses, spatial visualization, and correlation analysis to identify parameters that are most relevant for intake-water selection and salt-pond management.

This research is urgent because salt production in Madura is increasingly exposed to environmental variability, including changes in rainfall, temperature, sediment supply, and coastal activities [12], [13]. In addition, demand for better-quality salt requires more selective management of seawater intake, sediment control, and evaporation-pond operation [14]–[16]. Improvements in salt pond structures, filtration systems, and production technologies are also important factors supporting efficient salt production and maintaining raw material quality [17], [18]. A clearer understanding of local seawater properties can support practical decisions on where and when raw seawater should be collected for salt ponds.

This study aimed to inventory and analyze the physical properties of seawater used as raw material for salt ponds in the Padelegan coastal area. Specifically, it examined spatial variation in temperature, salinity, brightness, turbidity, TDS, TSS, viscosity, density, and SG; evaluated relationships among the measured parameters; and discussed their implications for salt-pond productivity and raw-material suitability.

2. Materials and Methods

This study used purposive sampling to select stations that represented the main seawater sources and environmental gradients around the Padelegan salt-pond area. Sampling was conducted at 15 stations on 9 August 2022 during flood tide and

under cloudy weather conditions. The stations covered river-influenced waters, estuarine areas, nearshore waters, and offshore waters. At each station, surface-water measurements were taken at 0–1 m depth, and water samples were collected in duplicate using a vertical water sampler for laboratory analysis.

2.1 In situ measurements

In situ measurements included temperature (°C), salinity (ppt), brightness/transparency (m), turbidity (NTU), and TDS (mg/L or ppt; ensure one unit is used consistently throughout the manuscript). Temperature was measured using Eutech DO 600. Salinity was measured using Atago Hand-Held Refraktometer. Brightness was measured with a Secchi disk, turbidity with LUTRON TU-2016, and TDS with TDS 80. Before field use, instruments were calibrated according to manufacturer procedures: the salinity meter/refractometer was checked with standard seawater or distilled water, the turbidity meter with standard turbidity solutions, and the TDS/EC meter with conductivity standards. Calibration dates and standard values should be reported here.

2.2 Ex-situ Measurements

Ex situ measurements were conducted in the laboratory using water samples collected during field sampling. TSS was determined gravimetrically by filtering a known volume of water through pre-weighed filter paper, drying the residue to constant weight, and calculating TSS in mg/L. Density (g/cm^3), and viscosity (cP). Laboratory analyses were performed in triplicate and mean values were used for statistical analysis.

• Quality control and instrument calibration

Field instruments were rinsed with distilled water between stations to avoid cross-contamination. Laboratory glassware and sampling bottles were cleaned before use, and samples were stored in clean containers before analysis. Sampling was conducted at 15 stations representing different water bodies and potential raw-water sources for salt ponds (Figure 1). Station coordinates were recorded using GPS. The sampling design aimed to represent water masses affected by land-based activities, estuarine mixing, nearshore processes, and offshore marine conditions. Water samples were collected from the surface layer (0–1 m), as it is the primary source of water entering shallow salt ponds.

Station classification should be based on field observations and map interpretation. For reproducibility, each station should be described by its latitude, longitude, sampling time, tidal condition,

weather condition, water depth, and environmental setting. This information is required to interpret spatial patterns in salinity, turbidity, and suspended

sediment because these parameters can change rapidly with tide and weather.

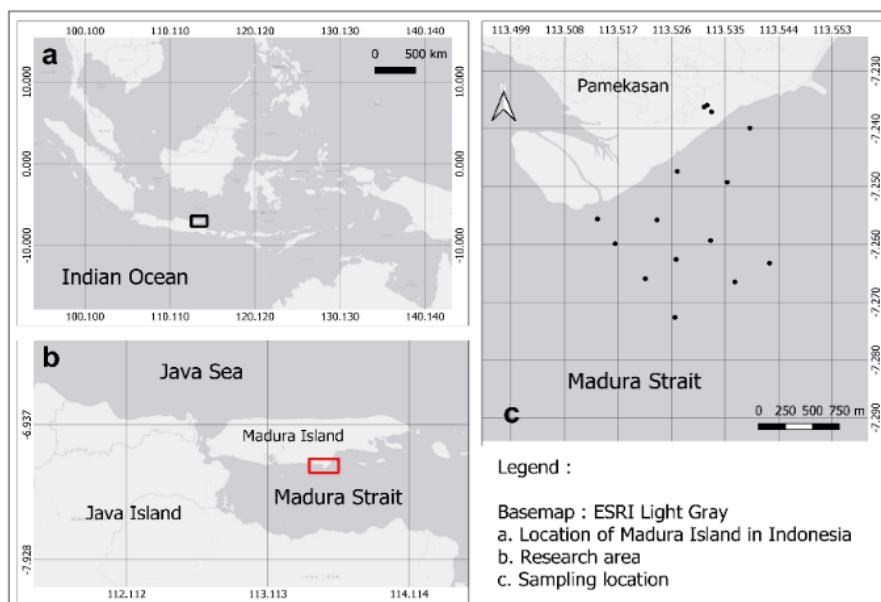


Figure 1. Study area and sampling stations in the Padelegan coastal area, Pamekasan, Madura.

- Data processing and analysis

All data processing and statistical analyses were conducted in RStudio using the R programming language [19]. Descriptive statistics were calculated for each parameter, Pearson correlation coefficients were computed to assess pairwise relationships among physical parameters, and spatial maps were generated using appropriate R packages such as ggplot2 and spatial interpolation/visualization packages. To avoid inconsistency, this revised manuscript reports RStudio/R as the analytical platform. The workflow consisted of data cleaning, unit checking, descriptive statistics, correlation analysis, and spatial visualization. Correlation strength was interpreted cautiously because Pearson correlation measures linear association and does not prove causality. Before resubmission, the raw dataset and R script should be archived or made available as supplementary material to support reproducibility.

3. Results

Surface seawater was measured in situ for temperature, salinity, brightness, turbidity, and TDS. Water samples were then collected for laboratory analysis of TSS, density, viscosity, and SG. The study area included waters influenced by tourism, fish landing activities, seaweed cultivation, rivers, estuaries, residential areas, and nearby salt ponds.

These activities may affect suspended sediment, turbidity, and dissolved material in raw seawater used for salt production. The results of the field and laboratory measurements are summarized in Figures 2 and 3.

Surface salinity ranged from 29.67 to 32.67 ppt. The lowest salinity values occurred at stations 7 and 8, which were located toward the open-sea area, whereas the highest value occurred at station 2 near land influence. This pattern indicates that salinity in Padelegan is not controlled only by distance from the coast; it may also reflect shallow-water evaporation, local circulation, river discharge, tidal phase, and possible return flow from salt-pond channels. Because average open-ocean salinity is approximately 35 ppt [8], the measured values represent slightly diluted to near-marine coastal water suitable for further concentration in solar salt ponds.

Brightness ranged from 0.35 to 0.80 m, with higher values generally observed at offshore stations. Turbidity ranged from 0.08 to 64.5 NTU and was higher at stations close to land, particularly stations 1, 2, and 3. This inverse relationship between brightness and turbidity indicates that suspended particles reduce water transparency. High turbidity and TSS near the coast are important for salt production because excessive suspended material may settle in intake channels and ponds, reduce brine clarity, and increase sediment-management requirements.

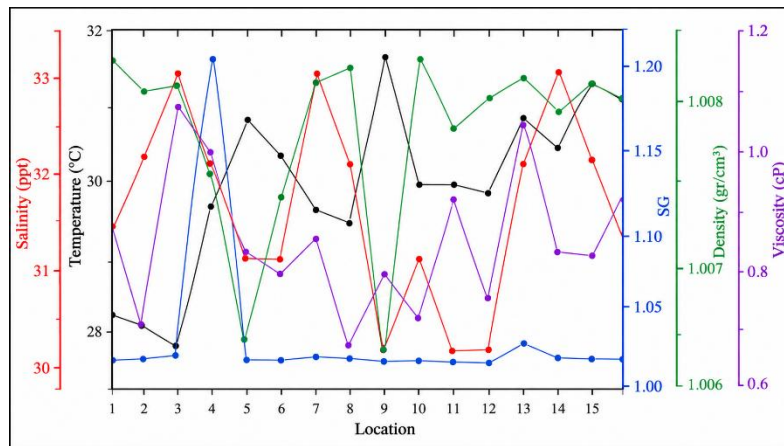


Figure 2. Station-wise variation in salinity (ppt), temperature (°C), density (g/cm³), viscosity (cP), and specific gravity (SG) at 15 sampling stations.

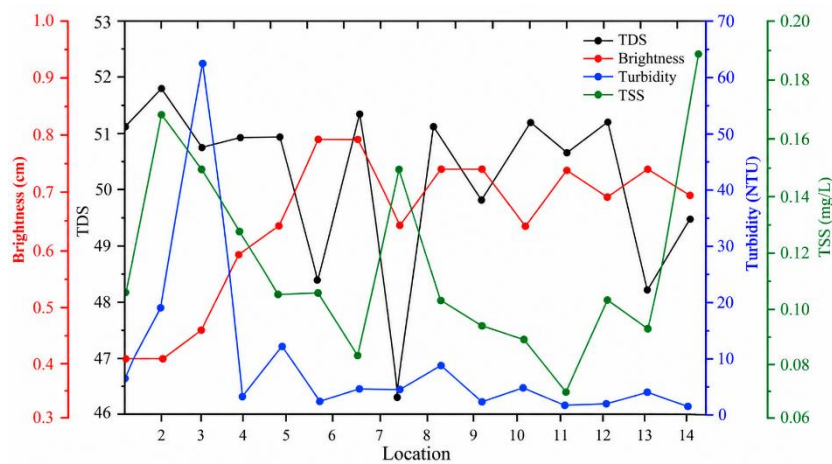


Figure 3. Station-wise variation in brightness/transparency (m), TDS (use consistent unit: mg/L or ppt), turbidity (NTU), and TSS (mg/L) at 15 sampling stations.

4. Discussion

4.1 Distribution of physical parameters

The spatial distribution maps show clear differences between land-influenced, estuarine, nearshore, and offshore waters. Temperature was highest at station 9, salinity was highest at stations 2 and 3, and density was highest at station 2. The

lowest temperature occurred at station 3, while the lowest salinity and density occurred at station 9. These spatial differences indicate that Padelegan waters are affected by a combination of tidal mixing, freshwater input, shallow-water heating, and local circulation rather than by a single onshore-offshore gradient.

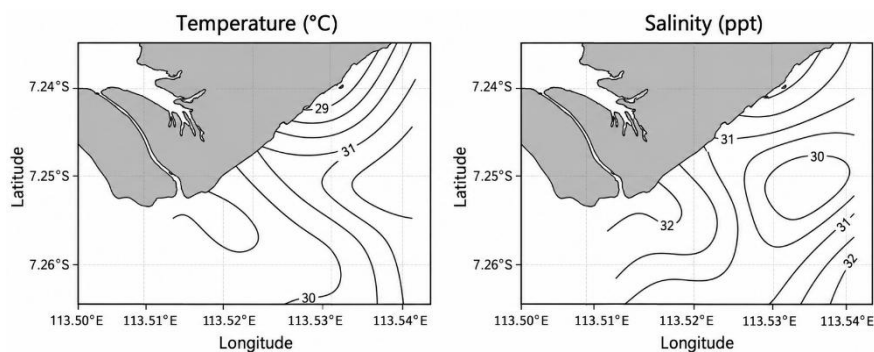


Figure 4. Spatial distribution of sea-surface temperature (°C) and salinity (ppt) in the Padelegan coastal area.

Water surface temperature ranged from 27.6 to 31.6 °C. Lower temperature near the estuary may be related to mixing with river water and differences in sampling time, whereas higher temperature toward offshore or shallow exposed areas may be associated

with stronger solar heating. Temperature is relevant to salt production because higher water temperature can increase evaporation rate, although the actual effect also depends on wind, humidity, rainfall, and pond design.

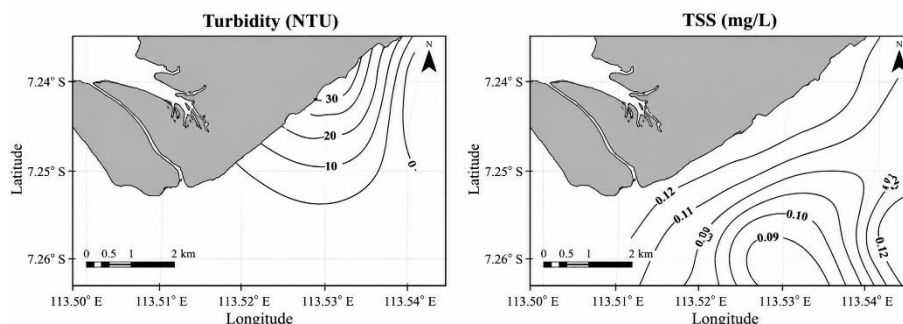


Figure 5. Spatial distribution of turbidity (NTU) and total suspended solids, TSS (mg/L), in the Padelegan coastal area.

Salinity ranged from 29.7 to 32.7 ppt across the 15 stations, with the highest values at stations 2 and 3. In general, offshore seawater often shows more stable marine salinity, whereas estuarine waters are commonly diluted by freshwater. However, the higher salinity observed at nearshore/estuarine stations in this study may be caused by local evaporation in shallow waters, restricted circulation, tidal trapping, or return flow from concentrated brine channels. Salinity does not precipitate or settle with depth; vertical and horizontal salinity differences are controlled by mixing, density stratification, freshwater input, and evaporation. This interpretation should be verified using tidal, rainfall, current, and water-depth data.

TSS values were higher near the coast and lower toward offshore waters. Nearshore waters are shallow and more strongly affected by wave-induced resuspension, river input, and land-derived sediment. Such processes are common

characteristics of shallow coastal systems, where hydrodynamic conditions influence sediment redistribution, suspended material concentration, and water quality variability [20]. For salt-pond management, high TSS is undesirable because suspended sediment can be carried into intake channels and evaporation ponds, increasing sedimentation, reducing brine clarity, and potentially affecting crystal quality. Therefore, raw seawater from high-TSS stations should pass through settling ponds or filtration channels before entering crystallization systems.

The lowest TSS values were observed at offshore stations, indicating lower suspended-particle concentration and potentially better raw-water clarity. However, offshore intake may require greater pumping distance and cost. The practical choice of raw-water intake should therefore balance water clarity, salinity, accessibility, and infrastructure constraints.

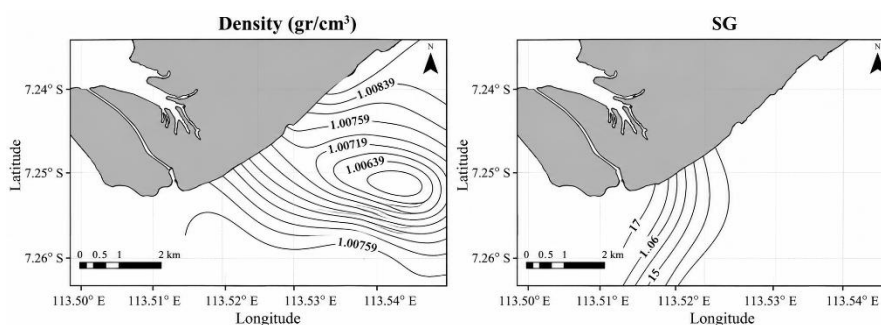


Figure 6. Spatial distribution of density (g/cm^3) and specific gravity (SG) in the Padelegan coastal area.

Density ranged from 1.006147 to 1.008313 g/cm^3 . The highest density occurred at station 2,

while the lowest occurred at station 9. In seawater, density is generally controlled by salinity,

temperature, and pressure, with higher salinity and lower temperature tending to increase density. The observed density pattern should therefore be interpreted together with salinity, temperature, and suspended/dissolved material rather than attributed

solely to nutrient input. For salt ponds, density and SG are useful indicators of brine concentration and can support decisions on when water should be transferred between evaporation ponds.

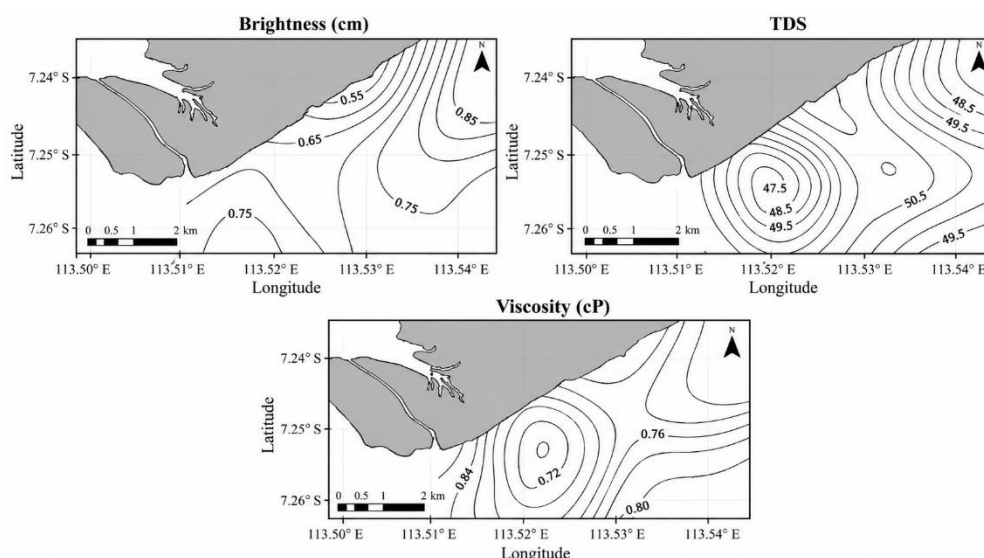


Figure 7. Spatial distribution of brightness/transparency (m), TDS (use consistent unit), and viscosity (cP) in the Padelegan coastal area.

Figure 7 shows that brightness generally increased from nearshore to offshore waters, while TDS and viscosity showed moderate spatial variability. Higher brightness offshore indicates lower suspended-particle concentration and better water clarity, which is favorable for salt ponds because clearer raw water reduces sediment accumulation in evaporation and crystallization ponds. TDS reflects dissolved constituents and is related to salinity, while viscosity reflects the combined influence of temperature and dissolved-solids concentration.

Nearshore waters were more strongly affected by terrestrial inputs and hydrodynamic disturbance. Lower brightness and higher turbidity near land indicate suspended sediments and organic matter from runoff, river discharge, resuspension, and coastal activities [21]–[24]. These conditions can reduce raw-water quality for salt ponds by increasing sediment loads and potentially introducing impurities. In operational terms, salt producers should avoid taking raw water during periods of high turbidity, after rainfall, or during strong resuspension events.

TDS represents dissolved substances rather than suspended particles. Lower TDS nearshore may indicate freshwater dilution, whereas higher TDS offshore reflects more stable marine water [25]. Because TDS and salinity influence the amount of

evaporation needed to reach brine concentration, stations with higher and more stable salinity/TDS are generally more efficient as raw-water sources, if turbidity and TSS remain low.

Viscosity showed a pattern broadly like TDS, suggesting an effect of dissolved-solids concentration. Nevertheless, viscosity is also temperature-dependent; higher temperature usually decreases viscosity, while higher dissolved-solids concentration can increase it [26]–[29]. For salt ponds, viscosity is less directly used than salinity or SG, but it can indicate changes in brine physical behavior during concentration. The interaction among temperature, salinity/TDS, and viscosity should therefore be discussed as a supporting indicator rather than as a primary productivity driver.

Overall, the physical characteristics indicate that offshore stations provide clearer seawater characteristics during the observation period, whereas nearshore and estuarine stations are more affected by sediment and land-derived inputs. Similar variations in coastal water characteristics have been reported in Indonesian coastal environments, particularly related to salinity variation and suspended material distribution [30], [31]. Coastal hydrodynamic conditions and human activities may further influence marine water quality characteristics [32], [33]. For salt-pond productivity, the most important practical implications are: (1) raw-water

intake should prioritize stations with adequate salinity, low turbidity, and low TSS; (2) intake should be avoided immediately after rainfall or during high-sediment conditions; (3) settling ponds or sediment traps should be used before water enters evaporation ponds; and (4) routine monitoring of salinity, turbidity, TSS, temperature, and SG should be conducted during the salt-production season.

4.2 Correlation among physical parameters

Table 2. Pearson correlation matrix among physical seawater parameters in the Padelegan coastal area.

Parameter	TDS	Temp	Salinity	SG	Bright	Turb	TSS	Density	Visc
TDS	1.00	-0.42	0.21	0.30	-0.32	0.22	0.31	0.35	0.09
Temp	-0.42	1.00	-0.64	-0.35	0.84	-0.55	-0.18	-0.60	-0.05
Salinity	0.21	-0.64	1.00	0.70	-0.68	0.34	0.34	0.59	0.11
SG	0.30	-0.35	0.70	1.00	-0.48	0.20	0.26	0.58	0.35
Bright	-0.32	0.84	-0.68	-0.48	1.00	-0.65	-0.30	-0.34	-0.15
Turb	0.22	-0.55	0.34	0.20	-0.65	1.00	0.47	0.05	0.17
TSS	0.31	-0.18	0.34	0.26	-0.30	0.47	1.00	0.03	0.06
Density	0.35	-0.60	0.59	0.58	-0.34	0.05	0.03	1.00	0.17
Visc	0.09	-0.05	0.11	0.35	-0.15	0.17	0.06	0.17	1.00

The strongest positive relationship was between brightness and temperature ($r = 0.84$), suggesting that clearer water may allow greater light penetration and surface heating, although station timing and spatial differences may also contribute. Salinity was strongly and negatively correlated with brightness ($r = -0.68$) and temperature ($r = -0.64$), while brightness was negatively correlated with turbidity ($r = -0.65$), indicating that suspended particles reduce water transparency. Salinity and density showed a moderate positive correlation ($r = 0.59$), which is consistent with the general dependence of seawater density on dissolved-salt concentration [25]. However, these relationships should be interpreted as associations within the observed dataset and should be validated with repeated temporal sampling, tidal information, and complete calibration records.

5. Conclusions

This study shows that the physical properties of seawater used as raw material for salt ponds in Padelegan vary spatially among land-influenced, estuarine, nearshore, and offshore stations. Salinity ranged from 29.67 to 32.67 ppt, temperature from 27.67 to 31.60 °C, brightness from 0.35 to 0.80 m, turbidity from 0.08 to 64.5 NTU, and density from 1.006147 to 1.008313 g/cm³. Offshore stations generally provided clearer and more stable seawater, whereas near-shore and estuarine stations were more influenced by suspended sediment and land-derived inputs. The positive correlation between brightness and temperature and the positive

Pearson correlation analysis was used to evaluate linear associations among the measured physical parameters: TDS, temperature, salinity, SG, brightness, turbidity, TSS, density, and viscosity. The complete Pearson correlation matrix is presented in Table 2. Correlation results were interpreted carefully because correlation does not indicate causation and may be influenced by sampling time, tidal stage, spatial autocorrelation, and the narrow range of some variables.

correlation between salinity and density indicate that physical parameters interact within the coastal system. Practically, salt-pond management in Padelegan should prioritize raw-water intake from stations with low turbidity and TSS, maintain sediment traps or settling ponds, and monitor salinity, temperature, turbidity, TSS, and SG routinely during the production season.

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