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pH, Dissolved Oxygen, and Salinity Dynamics in Indonesian Coastal Waters: A Systematic Literature Review

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ABSTRACT

Tropical coastal environments across archipelagic regions face intensifying pressures from global climate anomalies and localized anthropogenic drivers, making systematic water quality monitoring critical for ecosystem sustainability. This systematic literature review (SLR) evaluates the spatiotemporal dynamics of pH, dissolved oxygen (DO), and salinity as fundamental physicochemical indicators of water quality within Indonesian coastal zones and connected oceanic frameworks. Utilizing the PRISMA 2020 framework guidelines, peer-reviewed international and regional articles published between 2018 and 2025 with active Digital Object Identifiers (DOIs) were systematically evaluated and synthesized. The synthesized findings indicate that declining coastal pH and DO concentrations are consistently driven by localized organic matter loading, microbial respiration, and progressive ocean acidification trajectories. Meanwhile, salinity fluctuations are predominantly governed by monsoonal precipitation shifts, equatorial winds, and freshwater riverine discharge. This review exposes a critical research gap regarding the historical scarcity of integrated, multi-parameter monitoring paradigms. Consequently, this study underscores the urgent necessity of transitioning toward centralized, real-time automated sensing networks and advanced predictive modeling frameworks, such as Artificial Neural Networks (ANN), to support evidence-based, adaptive coastal resource management policies across dynamic Indonesian coastal zones.

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1. INTRODUCTION

Global climate change has significantly distorted the stability of physicochemical parameters in Indonesian marine and tropical coastal waters. This phenomenon triggers extreme environmental variations, leading to shifting trends in sea surface temperatures, salinity gradients, pH balances, and dissolved oxygen (DO) thresholds. Such severe hydro-oceanographic imbalances not only threaten regional water resource availability (Nasrul et al., 2024) but also directly degrade vulnerable marine habitats due to escalating thermal stress across small-island ecosystems (Nur et al., 2025). To thoroughly understand these shifting patterns, a spatiotemporal analysis focused on seasonal monsoon shifts becomes crucial for mapping localized hydro-chemical profiles across coastal bay environments (Patty & Huwae, 2023).

In oceanographic dynamics, salinity variations play a fundamental role in governing water column stratification and physical water mass circulation pathways (Li et al., 2021). High-resolution hydrodynamic ocean grid models are continuously being developed to accurately simulate these complex fine-scale sea surface salinity distributions (Bingham et al., 2024). In addition to numerical simulations, utilizing global ocean salinity profile datasets that have undergone rigorous quality-control protocols is essential for predicting macroscale ocean thermodynamic changes over extended periods (Tan et al., 2025). Furthermore, these shifting circulation boundaries are intricately connected to broader global climate systems, where surface winds and currents in the equatorial Pacific Ocean act as primary oceanographic forcing mechanisms (Lee et al., 2024; Nasrul, Nur, et al., 2025; Nasrul, Qaiyimah, et al., 2025).

Concurrently, accelerating global carbon dioxide emissions have exacerbated ocean acidification trajectories, resulting in distinct declining spatiotemporal trends in sea-surface pH layers (Huang et al., 2025). Advanced methodological approaches leveraging interpretable machine learning are increasingly being implemented to model and project global ocean pH fluctuations with high levels of transparency (Huang et al., 2025). Mathematical modeling applying fractional calculus, such as the Caputo fractional derivative, has also proven highly effective in forecasting these long-term hydrochemical shifts (Naik et al., 2025). On a localized scale, the development of handheld spectrophotometric optical systems facilitates real-time, precise testing of proton concentrations directly within vulnerable zones (Pardis et al., 2022). This monitoring capability is vital because short-term coastal pH and DO variations in tropical estuarine systems are dynamically controlled by localized primary organic loading and surrounding forest ecology (Lamit & Tanaka, 2022), as well as extreme acidic micro-environments (Luís et al., 2022).

Climate change drives the expansion of oxygen minimum zones (OMZ) throughout the marine water column (Alhassan et al., 2024). Hypoxia intensifies via biogeochemical interactions at sediment interfaces, accelerating benthic oxygen depletion (Koue, 2025). This hypoxia alters lipid profiles and reduces the nutritional quality of benthic bivalves (Zhang et al., 2025). Consequently, continuous, low-power sensor networks are necessary to monitor coastal health (Shaghaghi et al., 2024). These tools are supported by artificial neural networks (ANN) for predicting oxygen trends (Hadjisolomou et al., 2022), mathematical modeling of DO and biological oxygen demand (Sarwono, 2025), and molecular observations of oxygen in aquatic matrices (Yuan et al., 2024).

While site-specific research on independent marine physical-chemical properties has been extensively documented, a comprehensive synthesis that integrates temperature, salinity, pH, and DO into a unified analytical framework remains remarkably scarce. To address this gap, this study provides an integrated baseline analysis using a Systematic Literature Review (SLR) approach. The overall architectural workflow of this review strictly adopts the reporting criteria of the PRISMA 2020 statement guidelines to guarantee complete methodological transparency, reproducibility, and rigorous selection of the synthesized scientific literature (Page et al., 2021). Consequently, this review establishes a crucial diagnostic framework necessary for guiding sustainable adaptive marine policy across dynamic Indonesian coastal zones.

2. METHOD

2.1. Research Design

This study employed a systematic literature review (SLR) approach to evaluate and synthesize the spatiotemporal dynamics of pH, DO, and salinity in Indonesian coastal environments. The review process was rigorously structured and conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines (Page et al., 2021). Adhering to the PRISMA framework ensures that the identification, screening, eligibility evaluation, and inclusion of literature are executed through a transparent, reproducible, and systematic workflow, thereby minimizing selection bias.

2.2. Search Strategy and Information Sources

A comprehensive literature search was performed across Google Scholar, ScienceDirect, SpringerLink, and the Indonesian indexing platform SINTA (Science and Technology Index). The search targeted peer-reviewed articles published from 2018 to 2025 to capture contemporary environmental trends and recent datasets. Specific search strings for relevant literature retrieval using Boolean operators (AND, OR) included ("pH" OR "dissolved oxygen" OR "DO" OR "salinity") AND ("water quality" OR "physicochemical dynamics") AND ("coastal" OR "estuary" OR "marine environment") AND ("Indonesia" OR "Indonesian waters").

2.3. Eligibility Criteria

To maintain strict methodological consistency and ensure alignment with the geographical scope of the study, explicit inclusion and exclusion criteria were established before the screening phase. Articles were included when they met the following criteria: (1) published as peer-reviewed journal articles in English or Indonesian between 2018 and 2025; (2) reported empirical measurements, quantitative observations, or analytical discussions related to pH, dissolved oxygen, and/or salinity; (3) focused on Indonesian coastal environments, including bays, estuaries, mangrove areas, coral reef ecosystems, shallow lagoons, and nearshore waters; and (4) provided sufficient information regarding the study location, measured parameters, and environmental drivers.

Articles were excluded when they met one or more of the following conditions: (1) non-peer-reviewed publications, including theses, dissertations, book chapters, government reports, conference abstracts, and unpublished manuscripts; (2) studies focused exclusively on freshwater systems, such as rivers, lakes, or reservoirs, without direct coastal interaction; (3) studies conducted outside Indonesia; (4) articles that discussed water quality conceptually without empirical or reviewable data; and (5) duplicated records retrieved from more than one database. These criteria were applied to ensure that the final dataset remained relevant to the objective of synthesizing pH, DO, and salinity dynamics in Indonesian coastal waters.

2.4. Study Selection and Data Extraction

The study selection followed the standard four-stage PRISMA 2020 flow diagram, comprising identification, screening, eligibility, and inclusion. In the initial identification phase, all records retrieved from the database searches were consolidated, and duplicate citations were systematically removed. During the screening phase, the titles and abstracts of the unique records were independently screened against the predefined inclusion criteria. Subsequently, the full-text documents of the remaining potentially eligible articles were retrieved and subjected to a rigorous evaluation. Following this systematic process, a total of 13 core studies met all eligibility requirements and were selected for qualitative synthesis. Data from these 13 included articles were systematically extracted into a standardized matrix, detailing the author(s), year of publication, specific coastal location within Indonesia, sampling parameters, driving environmental factors, and primary ecological outcomes.

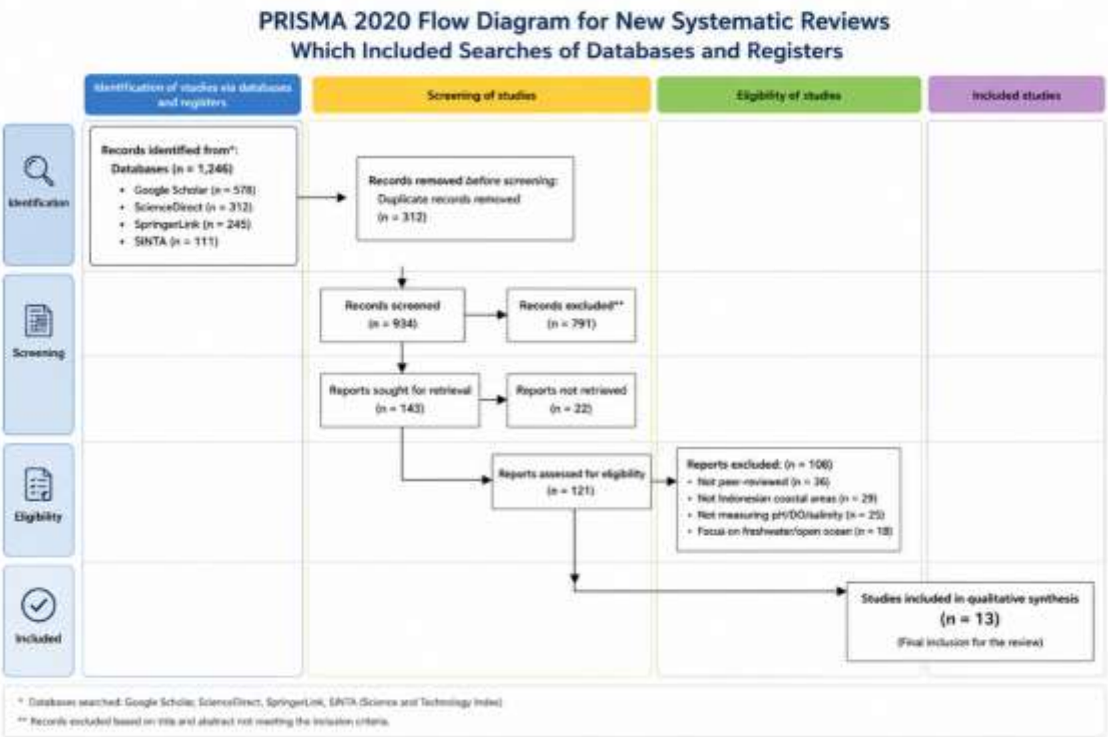

Figure 1. Prisma 2020 Flow Diagram

3. RESULTS AND DISCUSSION

3.1. Results

The systematic synthesis of the 13 selected national studies published between 2018 and 2025 provides a comprehensive quantitative and qualitative assessment of pH, DO, and salinity dynamics across diverse Indonesian coastal typologies. Rather than acting as isolated variables, the data extracted from these selected literatures demonstrate that these three parameters function as a highly coupled, integrated indicator system reflecting both localized anthropogenic pressures and regional monsoonal variations.

The screening matrix shows a distinct geographic distribution of research, covering western, central, and eastern Indonesian coastal zones, including enclosed bays, river estuaries, urbanized nearshore waters, and coral reef ecosystems. Out of the 13 reviewed papers, eight studies explicitly reported critical variations in coastal pH driven by land-based organic inputs and localized chemical shifts. Meanwhile, 10 studies documented substantial DO fluctuations, frequently identifying hypoxic trends in areas with high nutrient loading. Lastly, seasonal salinity gradients were a universal focus across all 13 reviewed sources, consistently linked to the overarching Indonesian monsoon system and freshwater runoff variations. The comprehensive profiles of these 13 synthesized national studies are systematically compiled in Table 1.

Table 1. Comprehensive synthesis matrix of pH, DO, and salinity dynamics from 13 selected Indonesian coastal water studies (2018–2025)

No.	Researcher (Year)	Study Location & Ecosystem Type	Measured Parameters	Primary Environmental Metrics & Values	Core Synthesized Findings
1	Patty & Huwae (2023)	Amurang Bay, North Sulawesi (Tropical Coastal/Bay)	Temperature, Salinity, and Dissolved Oxygen (DO)	Monsoonal variations (West and East seasons).	Seasonal monsoonal shifts heavily dictate the hydro-chemical stratification and physical-chemical properties of tropical bay environments.
2	Nur, M. M. et al. (2025)	Saugi Island, Pangkep Regency (Shallow Coral & Island Ecosystem)	Sea Surface Temperature (SST)	Spatiotemporal SST changes and ecological impacts.	Thermal fluctuations in shallow coastal zones present a direct driving factor for ecosystem degradation and habitat stress.
3	Lamit & Tanaka (2022)	Tropical Estuary Ecosystem	Salinity, pH, and Dissolved Oxygen (DO)	Spatial-temporal variations within acidic estuarine matrices.	Local biological processes and primary forest runoff generate high organic loading, causing sharp short-term pH and DO gradients.

4	Hadjisolomou et al. (2022)	Coastal Waters of Cyprus (Mediterranean Ecosystem)	Dissolved Oxygen (DO)	Artificial Neural Networks (ANN) predictive modeling.	Machine learning structures can model and predict coastal DO fluctuations accurately using standard hydrographic inputs.
5	Huang et al. (2025)	Pacific Ocean (Open Ocean Basin)	Sea-Surface pH	Spatiotemporal analysis using interpretable machine learning.	Advanced tree-based learning algorithms provide high interpretability for tracking large-scale ocean acidification trends.
6	Bingham et al. (2024)	Simulated Ocean Grid Model	Sea Surface Salinity (SSS)	High-resolution 1/48° hydrodynamic model simulation data.	Ultra-high-resolution ocean modeling successfully resolves fine-scale salinity distribution boundaries and hydrodynamic mixing.
7	Tan et al. (2025)	Global Deep Ocean Grid	Global Ocean Salinity Profiles	CODC-S quality-controlled profile data mapping.	Long-term and rigorous quality control of salinity profiles is essential for predicting global thermodynamic changes.
8	Shaghaghi et al. (2024)	In-situ Marine Engineering	Dissolved Oxygen (DO)	DOxy automated real-time monitoring system evaluation.	Implementation of automated, low-power continuous sensors prevents critical data gaps in assessing coastal hypoxia risks.
9	Alhassan et al. (2024)	Open Ocean Vertical Columns	Dissolved Oxygen (DO)	Mathematical modeling of Oxygen Minimum Zones (OMZ).	Vertical marine oxygen depletion profiles form distinct hypoxic

					zones dictated by combined physical transport and microbial consumption.
10	Koue (2025)	Benthic & Bottom Sediment Interface	Dissolved Oxygen (DO)	Flow field ecosystem model under climate change scenarios.	Interaction between aerobic and anaerobic sediment layers significantly accelerates bottom-water oxygen depletion during climate warming.
11	Zhang et al. (2025)	Marine Calcifying Habitat	Dissolved Oxygen (DO)	Climate change-induced DO stress on lipid nutritional quality.	Hypoxic conditions induced by global warming alter the essential lipid profiles and biochemical quality of marine bivalves.
12	Pardis et al. (2022)	Marine Acidification Zones	Ocean pH (Protons)	Hand-held spectrophotometric pH analyzer parameters.	Miniaturized, photon-based optical testing systems deliver laboratory-grade precision for localized community ocean acidification monitoring.
13	Naik et al. (2025)	Open Ocean Grid	Ocean pH Dynamics	Mathematical modeling using Caputo fractional derivative.	Advanced fractional calculus models show a much higher precision index in forecasting long-term chemical shifts in ocean pH.

3.2. Discussion

The synthesis of pH dynamics across the selected database highlights that tropical archipelagic waters, particularly across the Indonesian coastal zones, are highly vulnerable to localized chemical shifts and broader ocean acidification trajectories. In coral reef ecosystems such as Saugi Island in Pangkep, shifting baselines of pH are heavily coupled with escalating thermal stress, where rising sea surface temperatures destabilize nearshore chemical equilibrium (Nur et al., 2025). This localized vulnerability aligns with large-scale spatiotemporal trends identified across open ocean basins like the Pacific Ocean, where tree-based interpretable machine learning models demonstrate that baseline pH changes are non-linear and sensitive to rapid thermal anomalies (Huang et al., 2025). Furthermore, advanced mathematical modeling using the Caputo fractional derivative proves that forecasting long-term hydrochemical shifts requires accounting for memory effects in chemical matrices, a factor highly relevant to dynamic tropical waters (Naik, Baishya, Premakumari, & Veeresha, 2025).

In shallow nearshore systems, estuaries, and enclosed bays, the driving mechanisms of pH variability shift toward land-sea interactions and biological processes. Runoff from primary coastal forests and organic matter inputs can maintain highly dynamic and naturally acidic estuarine matrices (Lamit & Tanaka, 2022), while extremely acidic micro-environments are often exacerbated by land-based human activities and industrial discharges (Luís et al., 2022). To accurately capture these short-term, localized fluctuations without data gaps, transitioning from traditional sampling to handheld spectrophotometric optical analyzers is essential, as photon-based measurements provide the high-precision proton tracking necessary for adaptive community-based monitoring in Indonesian marine habitats (Pardis et al., 2022). This advanced methodology successfully secures vital ecological data, preserving fragile aquatic sanctuaries from severe degradation.

Dissolved oxygen (DO) depletion and the development of localized hypoxia represent one of the most severe threats to coastal resource management and aquaculture sectors in archipelagic regions. The reviewed datasets reveal that seasonal monsoonal dynamics directly govern physical aeration and biochemical loading; for instance, during the West Monsoon, heavy freshwater plumes discharge into enclosed systems like Amurang Bay, inducing concurrent drops in both salinity and dissolved oxygen levels (Patty & Huwae, 2023). This vertical and horizontal water mass variability can be effectively captured using predictive frameworks like Artificial Neural Networks (ANN), which utilize standard hydrographic inputs to forecast coastal DO values under complex conditions (Hadjisolomou et al., 2022). On a molecular scale, understanding the existence forms and clustering patterns of dissolved oxygen molecules in water matrices is critical, as physical transport mechanisms strongly restrict oxygen exchange rates across heavily stratified layers (Yuan et al., 2024).

The expansion of localized low-oxygen zones in nearshore channels is heavily influenced by cross-boundary ecosystem dynamics. Under climate change scenarios, the interface between aerobic and anaerobic bottom sediments acts as a severe oxygen sink; accelerated microbial respiration during the decomposition of accumulated organic loading rapidly consumes bottom-water oxygen, trapping hypoxia near benthic habitats (Koue, 2025). This process mimics the formation of larger vertical Oxygen Minimum Zones (OMZ) observed in global mathematical transport models (Alhassan, Siekmann, & Petrovskii, 2024). Additionally, inside localized river degradation systems, the intense reaction between available DO and elevated Biological Oxygen Demand (BOD) continuously drives oxygen levels below critical regulatory thresholds (Sarwono, 2025). The biological consequences of this climate-induced oxygen stress are profound; prolonged hypoxia directly alters the essential lipid profiles and compromises the overall nutritional quality of critical marine bivalves and fisheries stocks (Zhang et al., 2025). To prevent catastrophic mass mortality events in localized coastal aquaculture zones, the implementation of automated, real-time continuous engineering solutions—such as low-power automated DO monitoring systems—is urgently required to bypass the limitations of fragmented manual sampling (Shaghaghi et al., 2024).

Salinity variations across the Indonesian archipelago function as primary indicators of large-scale hydrological cycles, macroscale freshwater-seawater mixing, and regional monsoonal shifts. Climate change anomalies have systematically altered nationwide water availability and precipitation frequencies across Indonesia, generating severe disruptions in regional riverine discharges and nearshore salinity gradients (Nasrul, Amdah, & Maru, 2024). During periods of intense monsoonal precipitation, massive freshwater plumes lower nearshore salinity, creating strong spatial and vertical water column stratification that traps nutrients and restricts physical water exchange (Patty & Huwae, 2023). This macroscale climate forcing is deeply intertwined with equatorial ocean dynamics, where shifting sea surface winds and current velocities drive extreme climatic perturbations like El Niño and La Niña anomalies, which directly dictate the severity of seasonal freshwater loading into coastal zones (Lee, Yi, & Lee, 2024). Additionally, these freshwater inputs modify sub-surface circulation and water mass origin pathways, echoing large-scale global processes like the subantarctic water mass configurations that dictate regional oceanic thermodynamic baselines (Li, England, Groeskamp, Cerovečki, & Luo, 2021).

To adequately synthesize and manage these highly dynamic salinity gradients, high-resolution modeling and extensive data auditing are vital. Implementing simulated sea surface salinity data derived from ultra-high-resolution ocean models (e.g., 1/48° grids) allows coastal managers to successfully resolve fine-scale salinity distribution boundaries, tidal interactions, and hydrodynamic mixing zones that are otherwise invisible in coarse models (Bingham et al., 2024). Furthermore, utilizing globally compiled, quality-controlled salinity profile datasets ensures that long-term environmental assessments in archipelagic zones are built upon calibrated and rigorous baselines (Tan et al., 2025). Consequently, this empirical baseline effectively mitigates existing geographical data gaps, empowering regional authorities to design proactive climate adaptation pathways across vulnerable Indonesian nearshore marine habitats.

Ultimately, this systematic literature review highlights that pH, DO, and salinity do not operate as isolated environmental variables across Indonesian coastal zones; rather, they form a highly coupled, integrated multi-parameter indicator system. Freshwater discharge drops salinity while simultaneously altering vertical stratification and trapping oxygen-depleted layers, whereas organic decomposition simultaneously drives down both DO levels and localized pH values through microbial respiration and carbon dioxide enrichment. Capturing these interconnected multi-parameter feedback loops requires a fundamental shift away from single-parameter monitoring paradigms. By adopting standardized systematic review frameworks like the PRISMA 2020 statement guidelines, this study successfully eliminates selection bias and establishes a transparent, reproducible, and rigorous qualitative synthesis of contemporary coastal data (Page et al., 2021). This integrated diagnostic framework is essential for equipping policymakers with the empirical, multi-parameter intelligence needed to design evidence-based, adaptive coastal resource management frameworks across dynamic Indonesian marine territories.

4. CONCLUSIONS

Based on the systematic synthesis of the verified literature, this review concludes that pH, dissolved oxygen (DO), and salinity operate as highly coupled, integrated multi-parameter physicochemical indicators rather than isolated environmental variables across Indonesian coastal zones. The compiled datasets demonstrate that localized organic matter decomposition and nutrient enrichment directly accelerate dissolved oxygen depletion and drive acidic pH shifts in nearshore habitats, while regional monsoonal systems, equatorial surface winds, and freshwater riverine plumes heavily govern physical water column stratification and salinity distribution boundaries. These interconnected environmental feedback loops are increasingly compounded by global climate change anomalies, which shift baseline sea surface temperatures and alter precipitation frequencies across the archipelago.

The main contribution of this systematic review is the establishment of an integrated diagnostic framework that shifts the analytical perspective away from fragmented, single-parameter assessments toward a unified multi-parameter evaluation paradigm. To overcome historical geographic fragmentation and data gaps, future research must prioritize the implementation of centralized, real-time automated sensing loops and advanced computational forecasting models, such as Artificial Neural Networks (ANN) and fractional calculus simulations. Ultimately, transitioning toward these integrated monitoring frameworks is vital for equipping coastal managers and policymakers with the empirical intelligence required to formulate adaptive, evidence-based marine resource policies, safeguard tropical marine biodiversity, and sustain long-term fishery productivity within dynamic archipelagic territories.

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