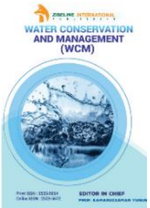
Water Conservation & Management (WCM)

DOI: http://doi.org/10.26480/wcm.04.2025.766.773

ISSN: 2523-5664 (Print)
ISSN: 2523-5672 (Online)
CODEN: WCMABD



RESEARCH ARTICLE

IMPACTS OF EL NIÑO AND MONSOONAL INTERACTIONS ON RIVER WATER QUALITY AND CAGE AQUACULTURE IN THE PAHANG RIVER, MALAYSIA

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Article History:

Received 11 September 2025
Revised 21 October 2025
Accepted 17 November 2025
Available online 17 December 2025

ABSTRACT

El Niño-induced warming in the central and eastern Pacific often triggers droughts and deteriorates freshwater quality across Southeast Asia, including Malaysia. This study aims to evaluate the impacts of *El Niño* and Northeast Monsoon dynamics on river water quality and their implications for freshwater cage aquaculture in the Pahang River. Specifically, it examines three 2023 climatic phases: (1) the Northeast Monsoon (January–March), (2) the *El Niño* period (April–October), and (3) their combined period (November–December). Monthly sampling across multiple sites (n = 96) was conducted to assess key water quality parameters. During the Northeast Monsoon (Jan–Mar 2023), all measured parameters remained within optimal ranges for freshwater fish, except phosphate levels (0.22 ± 0.11 mg/L). During the *El Niño* phase (Apr–Oct 2023), mean river temperature rose by 3 °C (28 ± 1 °C) with unionized ammonia at 0.013 ± 0.01 mg/L. The combined *El Niño*–Northeast Monsoon period (Nov–Dec 2023) demonstrated significant degradation in water quality: total suspended solids reached a maximum of 151.5 ± 93.2 mg/L, and ammonia concentrations increased to 1.08 ± 0.49 mg/L, while temperature fluctuated between 26 °C and 30 °C. These alterations adversely affect fish health by reducing dissolved oxygen levels and elevating nitrogen toxicity. The results highlight the considerable challenges that *El Niño* poses to the sustainability of aquaculture operations in the Pahang River. The implementation of effective mitigation strategies is imperative to protect the aquaculture sector in the region from climate-induced impacts.

KEYWORDS

Cage aquaculture, Climate Change, *El Niño*, Pahang River Water Quality, Northeast Monsoon

1. INTRODUCTION

Pahang State is located on the east coast of Peninsular Malaysia. It has extensive river systems and water bodies that provide a suitable habitat for freshwater fish. Particularly notable among these waterways is the Pahang River, which is located between latitudes N 2° 48' 45" and N 3° 40' 24", and longitudes E 101° 16' 31" and E 103° 29' 34". The Pahang River is the longest in Peninsular Malaysia, spanning a distance of 459 km. The catchment area of the Pahang River covers seven districts in Pahang, namely Maran, Jerantut, Bentong, Lipis, Temerloh, Bera, Cameron Highlands, as well as one sub-district in Kuantan, eleven sub-districts in Pekan, and two districts in Negeri Sembilan State, namely Jelebu and Kuala Pilah (Lim et al., 2020). The main source of this river originates from Mount Tahan, which stands 2,187 meters above sea level. The river begins at the confluence of the Jelai River and Tembeling River and flows eastward into the South China Sea.

The Pahang River is known for its extensive aquaculture activities. Cage aquaculture in the river plays a significant role in both the state and national aquaculture industries. With a total of 1,322 operators, the cage culture system in the Pahang River contributes to 73% of the state's freshwater aquaculture production. At the national level, Pahang accounts for 50% of cage aquaculture production, making it a vital sector for Malaysia's aquaculture industry. Remarkably, the state is responsible for 47% of the national production of sutchi catfish, a species highly valued in local markets (DOFM, 2024). Cage farming in the Pahang River is both economically vital and culturally significant sutchi catfish, a key species, is often featured in traditional dishes popular among the local community.

On a global scale, freshwater aquaculture has emerged as an essential source of protein and revenue, particularly within developing regions such as Southeast Asia (Anderson et al., 2017). However, it remains highly vulnerable to the effects of climate change, particularly within riverine

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Cite The Article: Muhamad Izzuan Razali, Rimatulhana Ramly, Azila Abdullah, Muhammad Syafiq Izzuddin Abdul Hadi, Mohd Firdaus Nawi, Nadia Sabri na Afandi, Muhammad Zahir Ramli, Mohd Fuad Miskon (2025). Impacts Of El Niño And Monsoonal Interactions On River Water Quality And Cage Aquaculture In The Pahang River, Malaysia. Water Conservation & Management, 9(4): 766-773.

systems where variation in flow, rainfall, and temperature fluctuations can significantly alter water quality and aquatic health (Whitehead et al., 2015). Consequently, understanding the interaction between climatic variability and aquaculture environments is a priority for ensuring the resilience and sustainability of this sector.

Malaysia experiences two main monsoon seasons: the Southwest Monsoon (May to September) and the Northeast Monsoon (November to March). The Northeast Monsoon, driven by cold air flows from Siberia, is the primary rainy season and brings heavy rainfall. This weather system brings significant rainfall, especially to Pahang and the east coast of Malaysia (Malaysian Meteorological Department, 2025). In Pahang, the Northeast Monsoon has a major impact on the climate and environment, increasing river discharge and often causing flooding and influencing the river ecosystem (Keya et al., 2024 ; Mohd and Mohd, 2020 ; Nur et al., 2023). Meanwhile, *El Niño* is a climate phenomenon manifesting warming sea surface temperatures in the central and eastern Pacific Ocean along the equator. It disrupts global weather patterns, typically occurring every 2 to 7 years and lasting 9 to 12 months (Haines and Lam,2023; NOAA,2024). In Southeast Asia, including Malaysia, *El Niño* is associated with reduced rainfall and increased temperatures (Golder, 2022). Media reports indicate that as of 2015, Malaysia has experienced 12 *El Niño* events, beginning with the first occurrence in 1951–1952 (The Star, 2023). The most severe *El Niño* event occurred in 1997–1998. In Pahang, reduced rainfall and rising temperatures frequently lead to lower river water levels, which in turn impact aquaculture, strain water resources, and disrupt local communities.

Climate change refers to a long-term shift in temperature and precipitation patterns primarily driven by human activities such as the combustion of fossil fuels and deforestation (Ali and Kamraju, 2023). Industrial advancement has driven climate change by increasing greenhouse gas emissions, particularly carbon dioxide (CO2), which significantly contributes to global warming (Othman and Tukimat, 2018). According to the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report, global surface temperatures have increased by approximately 1.1°C above pre-industrial levels, with prominent warming in recent decades due to anthropogenic greenhouse gas emissions (IPCC, 2021). Climate change has become a critical global issue due to its profound impacts on human life, the environment, and water resources (IPCC, 2022). Climate change poses a growing threat to freshwater aquaculture by altering water quality. Rising river temperatures reduce dissolved oxygen levels (Jane et al., 2021). While drought conditions concentrate pollutants, further stressing aquatic organisms (Awotunde, 2024). Shifting rainfall patterns contribute to runoff and contamination, affecting species sensitive to temperature and oxygen levels (Handisyde et al., 2016 ; Nadarajah and Eide, 2019).

The combined effects of *El Niño* and the Northeast Monsoon amplify these challenges. Monsoonal rainfall may increase sedimentation and nutrient loading (Muthoka et al., 2024). *El Niño*-driven warming can promote pathogen outbreaks and elevate ammonia and nutrient levels, heightening fish mortality risk (Subasinghe et al., 2019). While several studies have investigated the individual impacts of monsoonal patterns or *El Niño* events on Malaysian riverine systems, the combined effects of these climatic drivers, particularly in cage aquaculture systems, remain poorly understood. Focusing on the Pahang River during 2023, we evaluate water quality dynamics across three distinct climatic phases: (1) the Northeast Monsoon phase (January-March), (2) the *El Niño* event (April-October), and (3) their combined period (November-December). we specifically assess key water quality parameters and their implications for freshwater cage aquaculture sustainability, particularly on sutchi catfish (*Pangasianodon hypophthalmus*).

This study establishes empirical linkages between seasonal climate drivers and aquaculture-relevant water quality parameters, providing critical insights for adaptive management strategies to enhance climate resilience in freshwater cage aquaculture systems.

2. METHODOLOGY

2.1 Study Area

Field sampling was conducted at eight stations along the Pahang River, spanning five districts—Jerantut, Temerloh, Bera, Maran, and Pekan—to ensure broad representation of cage aquaculture environments across the river. While the study did not focus on spatial comparisons between sites, this distribution ensured comprehensive coverage of aquaculture areas from upstream to downstream. All sites were collectively analyzed to evaluate seasonal variations in water quality parameters. Detailed descriptions of the sampling locations are provided in Table 1 and illustrated in Figure 1.

Table 1: Description of sampling sites

Location no.	District	Site	Coordinate	Elevation (m)
1	Jerantut	Kampung Lada	03°57'58.50N 102°23'46.60"E	60
2	Temerloh	Kampung Tanjung Kubu	03°42'33.09"N 102°22'20.07"E	42
3	Temerloh	Kampung Kuala Kerdau	03°33'56.00N 102°24'05.07"E	41
4	Bera	Kampung Paya Panjang	03°20'06.02N 102°30'16.07"E	35
5	Maran	Kampung Pengkalan Balai	3°28'29.4"N 102°35'34.5"E	31
6	Pekan	Kampung Kuala Chini	03°27'06.50N 102°53'28.80"E	23
7	Pekan	Kampung Terlang	03°29'17.00N 103°07'06.00"E	19
8	Pekan	Kampung Tanjung Medang	3°32'29.4"N 103°20'23.4"E	10

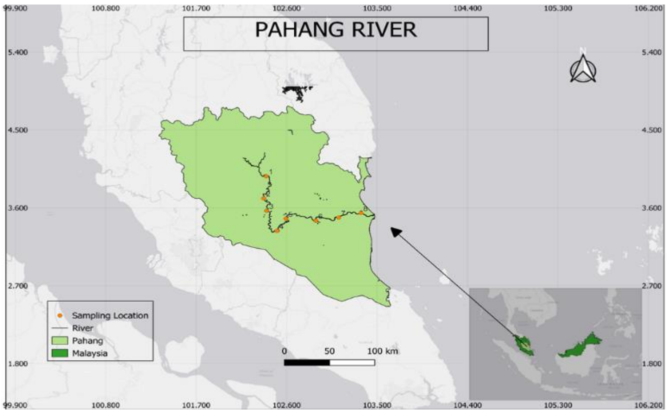

Figure 1: Location of sampling sites in Pahang River, Pahang, Peninsular Malaysia.

2.2 Seasonal Period Classification

Field sampling was conducted from January to December 2023. The data were categorized into three distinct seasonal periods based on prevailing climatic conditions (Figure 2). Seasonal periods in this study refer to particular climatic conditions. The first period, representing the Northeast Monsoon (NEM), occurred from January to March 2023. The second period, representing the *El Niño* conditions, occurred from April to October 2023. Finally, the third period, combining both *El Niño* and the NEM (*El Niño* + NEM), occurred from November to December 2023. This classification enabled a systematic assessment of water quality variations across different seasonal periods in the Pahang River. Seasonal classifications were determined based on authoritative sources of meteorological data, with the Northeast Monsoon period identified by the Malaysian Meteorological Department (Malaysian Meteorological Department, 2025) and the *El Niño* event defined using the Oceanic Niño Index (ONI) by the National Oceanic and Atmospheric Administration

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(NOAA, 2023).

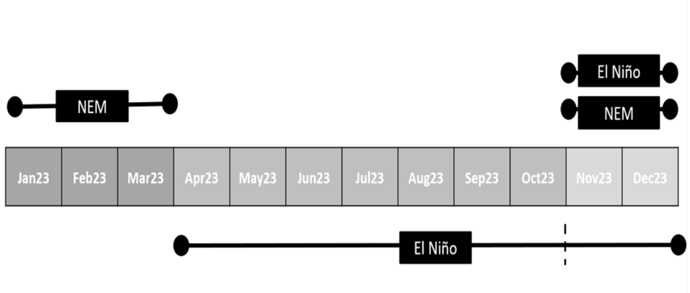

Figure 2: Seasonal period classification at Pahang River, Pahang

2.3 Sample Collection and Analysis

Water quality sampling was strategically conducted at three stations within each selected site to ensure systematic coverage of the cage aquaculture area and to obtain representative data reflecting its overall water quality conditions. The stations were positioned upstream (before the cage area), midcage (within the cage culture area), and downstream (after the cage area), following the approach proposed by (Harjoyudanto et al., 2020) (Figure 3). At each station, water samples were collected at the surface and 1-meter depth using a Wildco® water sampler (Yulee, FL, USA), thereby accounting for potential vertical variability in water quality. Duplicate samples were taken per station to ensure data reliability and placed into pre-cleaned 1 L screw-capped polyethylene bottles. Samples were immediately stored in a cool box at 4°C to preserve their integrity, in line with standard protocols recommended by (Baird and Bridgewater, 2017).. A total of twelve water quality parameters were analyzed. Water quality parameters were measured *in situ* using a handheld multiprobe meter (YSI, Yellow Springs, OH, USA), which included water temperature (°C), pH (1-14), and dissolved oxygen (DO) (mg/L). River depth and flow rate were recorded using a depth sounder (Laylin Associates, Orange, VA, USA) and a water flow probe (Fondriest Environmental Inc., Beavercreek, OH, USA), respectively. Laboratory analysis was conducted using a spectrophotometer (HACH Company, Loveland, CO, USA) to determine the concentrations of total suspended solids (TSS), total ammonia, nitrate, nitrite, phosphate, and alkalinity in water samples.

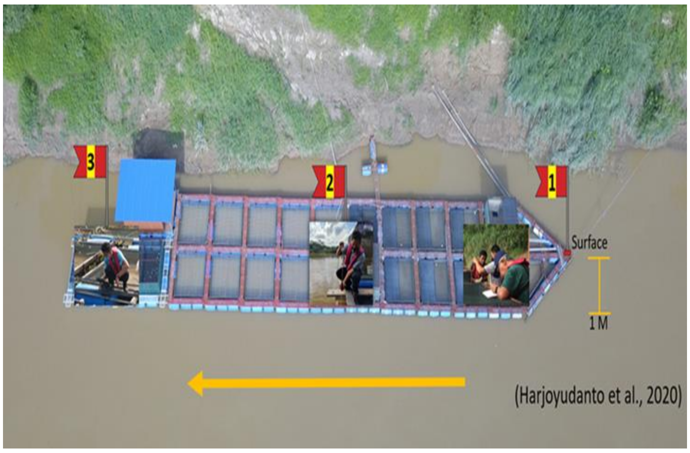

Figure 3: Water collection stations in the cage area

2.4 Data Analysis

Data analysis involved descriptive, inferential, and multivariate approaches. Descriptive results were expressed as mean ± standard deviation (SD) for each water quality parameter across the defined seasonal periods. Inferential analysis was conducted using one-way analysis of variance (ANOVA) to test for significant differences in water quality parameters across these periods, with post hoc comparisons performed using Tukey's test in SPSS Statistics (version 25). For the multivariate analysis, Principal Component Analysis (PCA) was conducted using OriginPro 2024 to identify key variables influencing seasonal variation and to discover patterns in water quality responses under different climatic influences. This study is based entirely on in situ field observations and does not involve computer-based or numerical simulations. Seasonal effects on water quality were assessed through statistical evaluation of field data collected under real monsoonal and *El Niño* conditions.

3. RESULTS

3.1 Water Quality and Seasonal Variation Characterization

The mean value of atmospheric, hydrological, and water quality parameter data from different season periods is presented in Table 2.

3.1.1 Atmospheric Parameters

The highest mean rainfall and relative humidity were observed during the *El Niño* + NEM period (21.75 ± 23.79 mm) and (88.1 ± 3.22%), respectively. In contrast, the lowest values were observed during the *El Niño* period, with rainfall of 10.89 ± 14.76 mm and relative humidity of 82.34 ± 2.10%. These variations in relative humidity closely corresponded to changes in rainfall. Statistical analysis confirmed significant differences ($p<0.05$) between the *El Niño* + NEM period and the other two periods. Wind speed was highest during the NEM period (4.75 ± 0.37 mph) and decreased significantly ($p<0.05$) during *El Niño* (3.52 ± 0.56 mph). The differences in wind speed appear to correspond with variations in relative humidity and rainfall, highlighting the role of atmospheric moisture transport.

3.1.2 Hydrological Parameters

The highest mean river depth was observed during the NEM period (3.9 ± 1.44 m) and was significantly greater than during *El Niño* (3.06 ± 1.36 m), ($p<0.05$). Meanwhile, the highest mean river flow rate was observed during *El Niño* + NEM (0.43 ± 0.25 m/s) and was significantly greater than during *El Niño* (0.32 ± 0.22 m/s). The observed patterns suggest a positive relationship between river depth and flow rate.

3.1.3 Temperature

The temperature for both air and river showed a similar trend. The highest mean air and river temperatures were observed during the *El Niño* period (28.22 ± 0.62°C) and (29.52 ± 1.10°C), respectively. Conversely, the lowest was observed during the NEM (26.08 ± 0.62°C) and (26.82 ± 0.47°C). The observed patterns suggest a positive relationship between air and river temperature. Statistical analysis confirmed significant differences ($p<0.05$) between the *El Niño* period and the other two periods.

3.1.4 Water Quality Parameters

The mean of DO levels ranged from 6.04 ± 1.11 mg/L (*El Niño*) to 6.54 ± 0.43 mg/L (*El Niño* + NEM), while the mean of pH ranged between 6.83 ± 0.43 (NEM) and 7.11 ± 0.32 (*El Niño*). Both parameters stayed within the optimum range for freshwater aquaculture (DO: >5 mg/L; pH: 6.5-8.5). The mean TSS levels ranged from 102.09 ± 47.72 mg/L (NEM) to 151.52 ± 93.24 mg/L (*El Niño* + NEM). Only the *El Niño* + NEM period exceeded the optimum range for freshwater aquaculture (25-150 mg/L), with a significant difference ($p<0.05$) compared to the other two periods. TSS levels showed a similar pattern with rainfall, suggesting a positive relationship between the two parameters. The nutrients collected in this study were ammonia, unionized ammonia, nitrate, nitrite, phosphate, and alkalinity. The mean ammonia levels ranged from 0.9 ± 0.41 mg/L (NEM) to 1.08 ± 0.49 mg/L (*El Niño* + NEM). Only the *El Niño* + NEM period exceeded the optimum range for freshwater aquaculture (0.7-1 mg/L), with a significant difference ($p<0.05$) compared to the other two periods. The unionized ammonia was maintained at a safe level (0.02 mg/L) at all periods. The mean nitrate levels ranged from 0.75 ±0.67 mg/L (NEM) to 0.87 ±0.69 (*El Niño* + NEM) while mean nitrite levels ranged from 0.00 ±0 mg/L to 0.01 ±0 mg/L during the same period. Both parameters stayed within the optimum range for freshwater aquaculture (nitrate: <7 mg/L; nitrite: <0.1 mg/L). The mean phosphate level ranged from 0.22 ±0.11mg/L (NEM) to 0.28 ± 0.14 mg/L (*El Niño*). Both *El Niño* and *El Niño* + NEM recorded values exceeded the optimum range for freshwater aquaculture (0.005–0.2 mg/L), with a significant difference ($p<0.05$) compared to the other period. The mean alkalinity level ranged from 24.35 ±5.15 mg/L (NEM) to 34.47 ±7.62 mg/L (*El Niño*). The alkalinity was maintained at a safe level (>20 mg/L) at all periods.

3.2 Relationship Between Water Quality and Seasonal Variation

The PCA produced two axes that cumulatively explained 100% of the variance in the dataset, with PC1 explaining 52.50% and PC2 explaining 47.50%.

3.2.1 PC1: Temperature-Related Parameters

PC1 was primarily associated with temperature-related parameters. Air temperature (0.34) and river temperature (0.34) had high positive loadings on this component, suggesting a strong correlation between temperature and other environmental variables. Additionally, parameters such as alkalinity (0.32), pH (0.30), and phosphate (0.30) demonstrated positive loadings, suggesting their association with temperature-driven environmental changes. The strong loading of unionized ammonia (0.32) in PC1 further indicates its relationship with river temperature and pH, emphasizing the influence of temperature and acidity on ammonia speciation in the river system. In contrast, depth (-0.34) was negatively correlated with PC1, suggesting that higher temperatures are typically associated with shallower depth.

3.2.2 PC2: Solids and Nutrient Parameters

PC2 was primarily associated with solids and nutrient parameters, with high positive loadings for TSS (0.36), ammonia (0.36), nitrate (0.36), and nitrite (0.34). The high loading of rainfall (0.30) in this component suggested a positive correlation with these solids and nutrient parameters. This finding indicated that rainfall plays a significant role in influencing the concentrations of solids and nutrients in the river.

3.2.3 Seasonal Associations

The PCA was further analysed using the biplot of the principal component analysis (PCA) results to illustrate the relationships between water quality and seasonal variation (Figure 4). El Niño, characterized by warmer conditions, is strongly aligned with the positive PC1 axis, confirming its association with elevated temperatures and related environmental changes. Meanwhile, the combined *El Niño* + NEM season clusters strongly aligned with the positive PC2, confirming its association with increased nutrient and particulate transport during this period due to rainfall. Meanwhile, the combined *El Niño* + NEM season clusters were strongly aligned with the positive PC2, confirming their association with increased solids and nutrients during this period, driven by enhanced rainfall.

Table 2: Measurement of atmospheric, hydrological, and water quality parameters at Pahang River, Pahang. Different superscripts indicated significant differences (p<0.05)

PARAMETER	NEM (Jan-Mar)	EL NIÑO (Apr-Oct)	EL NIÑO + NEM (Nov-Dec)	Optimum Range (freshwater aquaculture)
Rainfall (mm)	15.41±28.67^{a}	10.89±14.76^{a}	21.75±23.79^{b}	-
Relative Humidity (%)	83.42±1.79^{a}	82.34±2.10^{b}	88.1±3.22^{c}	**-**
Wind Speed (mph)	4.75±0.37^{a}	3.52±0.56^{b}	3.69±0.38^{c}	**-**
Depth (m)	3.9 ± 1.44^{a}	3.06 ±1.36^{b}	3.57 ±1.29^{a}	-
Flowrate (m/s)	0.37 ±0.28^{ab}	0.32 ±0.22^{a}	0.43 ±0.25^{b}	-
Air Temperature (°C)	26.08±0.62^{a}	28.22±0.62^{b}	26.51±0.83^{c}	-
River Temperature (°C)	26.82 ±0.47^{a}	29.52 ±1.10^{b}	27.99 ±0.99^{c}	25-32 (°C)
Dissolved Oxygen (mg/L)	6.27 ±0.66^{a}	6.04 ±1.11^{a}	6.54 ±0.43^{b}	>5 mg/L
pH	6.83 ±0.43^{a}	7.11 ±0.32^{b}	7.05 ±0.15^{b}	6.5-8.5
Total Suspended Solid (mg/L)	102.09 ±47.72^{a}	105.32 ±74.84^{a}	151.52 ±93.24^{b}	25-150 mg/L
Total Ammonia (mg/L)	0.9 ±0.41^{a}	0.94 ±0.54^{ab}	1.08 ±0.49^{b}	0.7-1 mg/L
Unionized Ammonia (mg/L)	0.007 ±0.01^{a}	0.013 ±0.01^{b}	0.011 ±0.01^{b}	<0.02
Nitrate (mg/L)	0.75 ±0.67^{a}	0.8 ±0.70^{a}	0.87 ±0.69^{a}	<7 mg/L
Nitrite (mg/L)	0.00 ±0^{a}	0.00 ±0^{a}	0.01 ±0.01^{b}	<0.1 mg/L
Phosphate (mg/L)	0.22 ±0.11^{a}	0.28 ±0.14^{b}	0.27 ±0.13^{b}	0.005-0.2 mg/L
Alkalinity (mg/L)	24.35 ±5.15^{a}	34.47 ±7.62^{a}	30.86 ±9.97^{a}	>20 mg/L

Table 3: Variables loadings with absolute values of 0.30 and above in bold. Factor loadings 0.30 and above in absolute value are considered to be significant (Elareshi, 2023)

Parameter	**PC1**	**PC2**
Air Temperature (°C)	**0.34**	-0.04
Rainfall (mm)	-0.21	**0.30**
Depth (m)	**-0.34**	-0.04
Flowrate (m/s)	-0.24	0.26

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Table 3 (cont): Variables loadings with absolute values of 0.30 and above in bold. Factor loadings 0.30 and above in absolute value are considered to be significant (Elareshi, 2023)

River Temperature (°C)	**0.34**	0.06
Dissolved Oxygen (mg/L)	-0.23	0.27
pH	**0.30**	0.19
TSS (mg/L)	-0.06	**0.36**
Ammonia (mg/L)	-0.02	**0.36**
Unionized Ammonia (mg/L)	**0.32**	0.14
Nitrate (mg/L)	0.06	**0.36**
Nitrite (mg/L)	-0.12	**0.34**
Phosphate (mg/L)	**0.30**	0.19
Alkalinity (mg/L)	**0.32**	0.14
Eigenvalue	8.40	7.60
Percentage variance explained	52.50%	47.50%
Cumulative variance explained	52.50%	100.00%

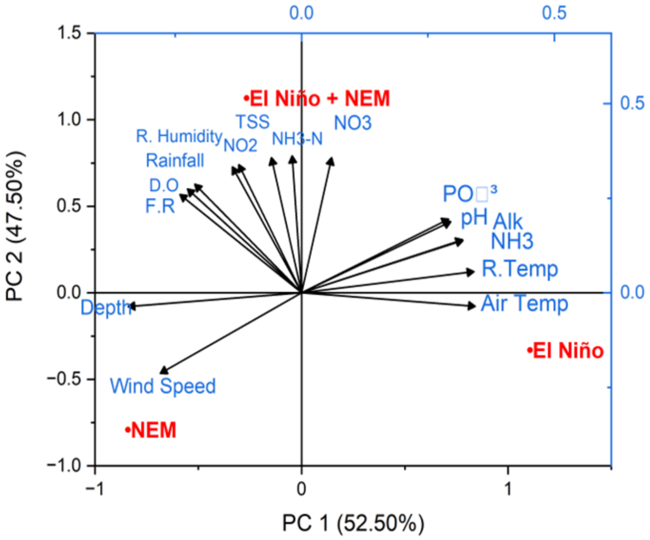

Figure 4: The relationship between water quality and seasonal variation using a biplot of the principal component analysis (PCA), where parameters include relative humidity (R. Humidity), rainfall (Rainfall), dissolved oxygen (D.O), flow rate (F.R), river depth (Depth), wind speed (Wind Speed), total suspended solids (TSS), nitrite (NO_2), ammonia (NH_3-N), nitrate (NO_3), phosphate (PO_4^{3-}), pH (pH), alkalinity (Alk), unionized ammonia (NH_3), river temperature (R. Temp), and air temperature (Air Temp)

4. DISCUSSION

The Northeast Monsoon occurs in Malaysia annually from November to March. The period from January to March (referred to as NEM in this study) represents the second half of the Northeast Monsoon, during which approximately 50% of the annual rainfall in East Coast states is typically received (Moten et al., 2014). Findings from this study indicate that the rainfall level was significantly lower ($p < 0.05$) during the NEM period compared to the first half of the Northeast Monsoon (November and December), referred to as *El Niño* + NEM in this study, These results are consistent with previous studies, which have reported that rainfall is more concentrated during the first two months of the Northeast Monsoon and gradually decreases during the second half of the season (January to March). Rainfall and relative humidity are closely interconnected meteorological phenomena that significantly influence each other. In this study, relative humidity showed a positive relationship with rainfall. During the NEM period, relative humidity was significantly lower ($p < 0.05$) compared to *El Niño* + NEM, which recorded a higher relative humidity. Higher humidity levels enhance precipitation efficiency (Silva et al., 2021). Their findings showed that local increases in relative humidity resulted in up to a 30% increase in instantaneous rainfall rates. Under normal circumstances, wind speed is higher during the first half of the Northeast Monsoon due to the pronounced pressure gradient between the Siberian High and the equatorial low-pressure belt (Geetha and Raj, 2021). However, our findings indicate otherwise, as wind speed during the NEM period (January to March) was recorded significantly higher ($p < 0.05$) compared to *El Niño* + NEM (November to December). This difference could be attributed to the influence of *El Niño*. During El Niño events, sea surface temperatures (SSTs) in the central and eastern Pacific Ocean rise, leading to a reduction in the east-west pressure gradient that drives the Walker circulation. This weakening of the Walker circulation results in diminished trade winds, which are typically strong under non-*El Niño* conditions (Falster et al., 2023). Consequently, the reduced trade wind activity during *El Niño* may explain the lower wind speeds observed during the *El Niño* + NEM period. During the NEM period, all water quality parameters recorded values within the optimum range for freshwater aquaculture except for phosphate (0.005-0.2 mg/L). The phosphate levels recorded exceed the optimum range for all other periods. The high levels of phosphate in the Pahang River can be attributed to extensive agricultural activities along the river's banks from upstream to downstream. This assertion is supported by several studies that highlight the impact of agricultural practices on water quality, particularly in terms of nutrient runoff. Agricultural activities often involve phosphate-rich fertilizers, which can leach into water bodies during rainfall, raising phosphate levels. Variables like phosphate are key to understanding river ecology, suggesting that agricultural runoff significantly impacts the Pahang River's water quality (Rashid et al., 2018). Malaysian rivers, particularly those in agricultural areas, often experience pollution from runoff containing high phosphate levels (Kozaki et al., 2016). The findings of this study highlight that the highest wind speed, coupled with lower levels of rainfall, relative humidity, and phosphate than *El Niño* +NEM, are characteristic of NEM.

During the *El Niño* period (April to October), rainfall, relative humidity, and wind speed were observed to be the lowest compared to other periods. During *El Niño* events is primarily linked to alterations in atmospheric circulation patterns (Iskandar et al., 2019). The disruption of the Walker circulation suppresses convection and cloud formation, thereby leading to diminished precipitation. As rainfall decreases, the amount of moisture available in the atmosphere also declines, resulting in lower relative humidity levels (Jackson et al., 2025). Slower wind speeds during the El Niño period significantly affect water mixing, which impacts oxygen distribution in aquatic systems (Mariani et al., 2018). This could explain why DO levels were observed to be the lowest during this period. Conversely, air temperature was observed to be the highest as compared to the other periods. *El Niño* is characterized by elevated sea surface temperatures (SST). Heating of sea surface temperature in the central and eastern Pacific Ocean typically increases the tropically averaged tropospheric temperature, which can lead to warmer air temperatures globally, including Malaysia (Urabe et al., 2017 ; Tan et al., 2021). As a result of elevated air temperature, river temperature also increases. The river temperature was significantly higher during this period ($p<0.05$) compared to the other two periods. A notable 3°C rise was observed compared to the non-*El Niño* period. According to Itsukushima et al. (2024), air temperature and other factors like land use significantly influence rising monthly water temperature in rivers. The increase in river temperature has multiple impacts on water quality. Higher temperatures, the saturation concentration of dissolved oxygen reduces, leading to lower overall DO levels in the water (Rajesh and Rehana, 2022). This relationship is critical because warmer water can hold significantly less oxygen than cooler water, which can lead to hypoxic conditions, thus lowering fish metabolism (Agarwal et al., 2024). The DO levels in this study were significantly lower ($p<0.05$) compared to the other periods, but remained within the optimum range for freshwater aquaculture. Increased river temperature can enhance the rate of evaporation, leading to a reduction in water volume or a decrease in river depth (Buitink et al., 2020). This phenomenon was observed in our study, where the river depth was recorded as significantly shallower ($p<0.05$) compared to the other two periods. Consequently, the reduced river volume reduced the dilution of water parameters (Hübner and Schwandt, 2018). Phosphate levels were recorded as significantly higher ($p<0.05$) compared to the NEM period, likely due to the effects of reduced dilution. These levels also exceeded the optimum range for freshwater aquaculture. The pH levels showed a significant increase ($p < 0.05$) during the El Niño period compared with the other two periods. In contrast, the decomposition of organic matter by microorganisms produces organic acids, which can significantly lower the pH of the surrounding water (Boyd 2015). This organic material typically originates from surface runoff entering the river during rainfall. The reduced rainfall during El Niño resulted in less organic material being introduced into the river, leading to higher pH levels. The combined effects of elevated pH and temperature during this period led to higher levels of unionized ammonia in the river (Maven's Notebook, 2025; Ng et al., 2018). In farm-scale recirculating aquaculture systems (RAS) for rainbow trout (*Oncorhynchus mykiss*), unionized ammonia (NH_3) is approximately 100 times more toxic than its ionized form (NH_4^+), with toxicity increased under elevated temperature and pH conditions (Becke et al., 2019). Chronic exposure to unionized ammonia exceeding 0.0125 mg/L resulted in gill damage, suppressed growth, and increased mortality. In this study, unionized ammonia is associated with El Niño, as shown in Figure 4. However, the level is still within the optimum range for freshwater aquaculture (<0.02 mg/L). The findings of this study reveal that the highest levels of air temperature, river temperature, pH, dissolved oxygen, phosphate, and unionized ammonia, alongside the lowest levels of rainfall, relative humidity, wind speed, and depth, are distinctive characteristics during the El Niño period. Prolonged exposure to high temperatures can also result in thermal stress, leading to decreased oxygen levels in the water and increased susceptibility to diseases (Li et al., 2023). Not only that, the combination of high temperatures and low water levels can lead to higher concentrations of ammonia and other toxic substances, further stressing fish populations (Meng et al., 2019).

The El Niño + NEM period (November to December) reflects the combined effects of the El Niño event and the Northeast Monsoon. This period recorded the highest rainfall compared to the other two periods, with a significant difference ($p < 0.05$). This can be attributed to the heavier rainfall typically expected during the first half of the Northeast Monsoon (November to December). The findings also indicate that, despite the El Niño event, rainfall during this period remained higher compared to the Non-El Niño period, NEM. Consequently, relative humidity, depth, and flow rate also recorded significantly higher levels ($p < 0.05$) than the other two periods. These parameters have been shown to have a positive relationship with rainfall precipitation, as documented by (Tudorache, 2018). As a result of higher rainfall and relative humidity, air temperature was significantly reduced ($p < 0.05$) compared to the El Niño period. Parameters such as air temperature, relative humidity, and rainfall exhibited negative correlations, suggesting that as rainfall increases, air temperature may decrease due to the cooling effects of moisture in the atmosphere (Liu et al., 2022). Low air temperatures directly reduce river temperature, as mentioned by (Itsukushima et al., 2024). During the El Niño + NEM period, river temperatures fluctuated between 26°C and 30°C. The combined effects of low river temperature, higher flow rate, and elevated depth contributed to improved DO levels in the river. In this study, DO was significantly higher ($p < 0.05$) compared to the other two periods, emphasizing the influence of hydrodynamic and thermodynamic factors on oxygen availability in aquatic systems (Konan et al., 2023; Gelca et al., 2015). Notably, DO levels during this period remained within the optimum range for freshwater aquaculture (>5 mg/L). TSS was significantly higher ($p < 0.05$) during this period compared to the other two periods, slightly exceeding the optimum range for freshwater aquaculture (25–150 mg/L). TSS refers to the particles and materials suspended in water, typically more than 2 µm in size, which can significantly impact water quality. Elevated levels of TSS can lead to detrimental effects on fish physiology and health. Recent studies that concentrations of TSS as low as 100 mg/L can damage gill structures in adult zebrafish, leading to reduced ion transporter activity and alterations in gill morphology (Montoya et al., 2024). The elevated level of TSS during this period can be attributed to elevated rainfall. High-intensity rainfall events are closely associated with increased runoff and sediment yield, leading to elevated total suspended solids (TSS) concentrations in river systems (Zhang et al., 2021). In addition to TSS, the increase in ammonia and other nutrients such as nitrate, nitrite, and phosphate during this period can be attributed to higher rainfall. Heavy rainfall increases surface runoff, which transports nutrients from agricultural and urban areas into rivers (Zhao et al., 2024). In this study, ammonia and phosphate levels slightly exceeded the recommended range for freshwater aquaculture (ammonia: 0.7–1 mg/L; phosphate: 0.005–0.2 mg/L), while nitrate and nitrite concentrations remained within the optimum range for freshwater aquaculture (nitrate: 7 mg/L; nitrite < 0.1 mg/L). The findings of this study reveal that the highest levels of rainfall, relative humidity, depth, flow rate, dissolved oxygen, total suspended solids (TSS), ammonia, and temperature fluctuation are distinctive characteristics during the combined effect of El Niño + NEM. Elevated water temperatures during El Niño events, intensified by NEM-induced variations, significantly impact fish physiology, leading to thermal stress that affects metabolic rates, growth, reproduction, and immune responses (Anett et al., 2018 ; McCabe, 2023).

5. CONCLUSION

This study demonstrated that the El Niño phenomenon in 2023 significantly affected the water quality of the Pahang River, with a notable increase of approximately 3°C in water temperature. This thermal shift contributed to reduced dissolved oxygen (DO) levels and elevated concentrations of unionized ammonia, both of which have direct implications for fish health and aquaculture viability. The combined effects of El Niño and the Northeast Monsoon (NEM) further exacerbated these conditions by increasing total suspended solids (TSS) and ammonia concentrations, and causing temperature fluctuations. These findings show that extreme weather events, especially El Niño and the seasonal monsoon, can disturb important water quality conditions needed for sustainable cage aquaculture. Therefore, continuous monitoring and adaptive management strategies are crucial to mitigating the impacts of climate variability on river-based aquaculture systems in the region

ACKNOWLEDGEMENT

We would like to express our sincere gratitude to the Department of Fisheries (DOF) Pahang for their valuable cooperation and collaborative support. We also acknowledge the Institute of Oceanography and Maritime Studies (INOCEM) for providing laboratory facilities for the analytical work. Special appreciation is extended to Dr. Siti Zahrah Abdullah and Mr. Zulkafli Rashid for their support, assistance, and contributions throughout the study.

FUNDING

Financial support for this work was provided by grant 40170502 from the Development Fund, Department of Fisheries (under 12th Malaysia Plan), Ministry of Agriculture and Food Security (MAFS), Malaysia.

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Cite The Article: Muhamad Izzuan Razali, Rimatulhana Ramly, Azila Abdullah, Muhammad Syafiq Izzuddin Abdul Hadi, Mohd Firdaus Nawi, Nadia Sabrina Afandi, Muhammad Zahir Ramli, Mohd Fuad Miskon (2025). Impacts Of El Niño And Monsoonal Interactions On River Water Quality And Cage Aquaculture In The Pahang River, Malaysia. Water Conservation & Management, 9(4): 766-773.

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