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RESEARCH

# Variation on water quality of Kerangas forest streams due to invasion of *Acacia*

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**Abstract** *Acacia* invasion has shown a negative impact on the water resources of forest streams. Therefore, studies need to be conducted demonstrating the importance of managing invasive species to preserve stream and forest ecosystems. This study investigates the effects of *Acacia* invasion on the water quality of Kerangas forest streams in Brunei. Water samples were collected from an *Acacia*-invaded (IN) stream and a non-invaded (NIN) stream during the dry season at three locations along each stream. Water properties, including pH, conductivity, salinity, total dissolved solids (TDS), phosphate, nitrate, ammonia, and nitrite, were analyzed using in situ and laboratory methods. The results showed that *Acacia* invasion significantly increased pH (from 4.01 to 5.68), nitrate (by 256%), and phosphate (by 250%) levels, while reducing conductivity (by 208%) and salinity (by 20%) compared to non-invaded streams. These findings suggest that *Acacia* invasion alters water chemistry, potentially posing risks to aquatic ecosystems. Effective management strategies, such as controlling *Acacia* spread and restoring native vegetation, are essential to mitigate these impacts and preserve forest water resources.

**Keywords** Invasive species · Dry season · Forest stream assessment · PH level · Environmental impact · Kerangas forest

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## Introduction

Invasive alien plant species are increasingly recognized for their substantial impact on stream ecosystems, affecting both physical and chemical properties. These plants disrupt water flows, reduce stream discharge, and alter soil physico-chemical characteristics, leading to significant changes in stream ecology (Chamier et al., 2012; Maitre et al., 2015; Ruwanza & Dondofema, 2019). The invasion of riparian habitats can shift in-stream community structures, reduce biodiversity, and disrupt ecological processes (Ferreira et al., 2021; Greenwood et al., 2004; Lecerf et al., 2007). Additionally, invasive plants can alter soil properties, nutrient cycling, and microbial communities, which in turn affect the overall health and functionality of streams (Qu et al., 2021; Vujanović et al., 2022). Such alterations in riparian vegetation can have profound effects on stream baseflow and ecosystem efficiency (Mineau et al., 2012; Vanderklein et al., 2013). Therefore, understanding the effects of invasive alien plants on stream physical and chemical

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properties is crucial for effective stream management and conservation efforts.

*Acacia* invasion significantly impacts water quality by altering nutrient cycling and increasing nitrogen and phosphorus concentrations in groundwater, leading to potential issues like eutrophication (Chamier et al., 2012; Foden et al., 2010; Wang et al., 2023). These changes degrade water quality, threaten native plant species, and disrupt overall ecosystem health, making water less suitable for human and ecological use. Invasive Acacias, resistant to environmental factors like drought and pests (Lorenzo et al., 2010), often displace native vegetation, reduce biodiversity, and increase water demand, ultimately decreasing soil water availability and altering stream flow (Le Maitre et al., 2011; Dye & Jermain, 2004).

*Acacia* invasions also alter aquatic conditions by raising pH, reducing ammonium content through processes like nitrification, and increasing total dissolved solids (Pereira et al., 2021). Elevated nitrogen and phosphorus levels from *Acacia* litter deposition can harm aquatic ecosystems, reducing biodiversity and productivity by encouraging nutrient accumulation (Chislock et al., 2013; Forrester et al., 2010). These changes negatively affect stream biodiversity and aquatic life, such as fish populations, further emphasizing the need to understand and manage the impacts of *Acacia* invasions (Moyle & Leidy, 1992).

The Kerangas forest is a unique forest in the world consisting entirely of Kerangas trees (Newbery et al., 1986). A Kerangas tree is a small, shrubby tree that grows in sandy soils (Din et al., 2015). The forest is also home to a variety of other plants and animals (Jermy, 1983). The Kerangas forest in Brunei Darussalam is threatened by the invasion of *Acacia* trees (Ibrahim et al., 2021). Acacias are large, fast-growing trees that are usually difficult to kill (Hegde et al., 2013). Brunei Darussalam *Acacia* trees are native to Australia and were introduced in the mid-1990s (Osunkoya & Damit, 2005). From our observation of the Kerangas forest where the *Acacia* has been introduced, the trees form dense stands that limit sunlight and air from reaching the ground below. It is reported that these invasive trees form dense canopies that block sunlight, suppress native vegetation, and reduce soil moisture availability, further stressing an already fragile ecosystem (Rochimi et al., 2021). Despite its significance, limited studies have explored the impact of *Acacia* invasion especially on the water quality of Kerangas streams, particularly in Brunei Darussalam. Understanding these impacts is crucial for informing forest management and conservation practices in Southeast Asia. The invasion of *Acacia* spp. into sensitive ecosystems such as the Kerangas forest presents significant challenges for forest management and conservation. By disrupting nutrient cycling and elevating nutrient levels in streams, these invasive species threaten aquatic ecosystem health and biodiversity (Terreaux & Lescot, 2019). Addressing these invasions is critical for maintaining the ecological balance and functionality of riparian habitats.

This study investigates the effects of *Acacia* invasion on water quality in Kerangas forest streams. By comparing an *Acacia*-invaded stream to a non-invaded control stream, we aim to elucidate how *Acacia* invasion alters key water quality parameters such as pH, conductivity, salinity, and nutrient levels. The findings contribute to a broader understanding of the ecological consequences of invasive species in Southeast Asia, providing insights into managing and mitigating their impacts on forest ecosystems. We thus hypothesize that water quality will be affected in terms of pH, conductivity, salinity, total dissolved solids, phosphate, nitrate, ammonia, and nitrite due to the characteristics of *Acacia*, particularly its leaf nutrient content and root absorption. We also hypothesize that the chemical properties of the water in the Kerangas forest will be affected by the invasion of the acacia due to the nitrification process. We have formulated two research questions:

1. Does *Acacia* invasion alter water properties (pH, conductivity, salinity, total dissolved solids, $NO_3^-$, $NH_4^+$, $PO_4^{3-}$) in water stream in heath forests?
2. Does the strength and direction of relationships between water properties in invaded versus non-invaded (NIN) forests differ and how are these relationships influenced by the dimensionality of soil water properties?

The research questions are vital for understanding the impacts of *Acacia* invasion on the unique and sensitive Kerangas forest ecosystem. By investigating changes in water properties (pH, conductivity, salinity, and nutrient levels) and relationships between these properties, the study highlights how invasive species disrupt nutrient cycling, water chemistry, and biodiversity. Elevated nitrate and phosphate levels may indicate eutrophication and microbial activity shifts, while hydrological changes from Acacia's water consumption could exacerbate water scarcity. The findings provide insights for managing invasive species, conserving biodiversity, and guiding policy to protect the ecological health of Kerangas forests and similar habitats in Southeast Asia.

## Materials and Methods

### Description of study area and water sampling

The study was conducted in the Kerangas Forest Reserve, located approximately 5 km from the Universiti Brunei Darussalam, Brunei (Fig. 1). The forest lies between latitudes 1°30′N and 2°00′N and longitudes 103°00′E and 110°00′E, with a topography primarily consisting of small hills. The region experiences a humid tropical climate with an annual rainfall of approximately 1600 mm (Department of Agriculture and Agrifood, unpublished data). The dominant tree families in the area are Dipterocarpaceae, followed by Myrtaceae, Anacardiaceae, and Guttiferae species. The soils are well-drained, acidic, and nutrient poor, characterized by a sandy texture (Ibrahim et al., 2023). These characteristics make the ecosystem particularly sensitive to external disturbances such as invasive species.

The *Acacia*-invaded (IN) stream was characterized by approximately 80% *Acacia* coverage within a 20-m buffer zone along both streambanks, while the non-invaded (NIN) stream showed no visible *Acacia* within the same buffer. This evaluation was limited to the riparian zone due to its direct influence on water quality through litter deposition and nutrient cycling. Water samples were collected monthly during the dry season at three stations (upstream, midstream, and downstream), spaced approximately 200 m apart. Each station was selected to capture spatial variability but was otherwise similar in stream morphology and riparian vegetation. Surface water samples were taken to ensure consistency, with three replicates collected for each parameter. The streams were narrow (average width: 1.5 m) with depths ranging from 20 to 50 cm, and the measured reach extended approximately 600 m.

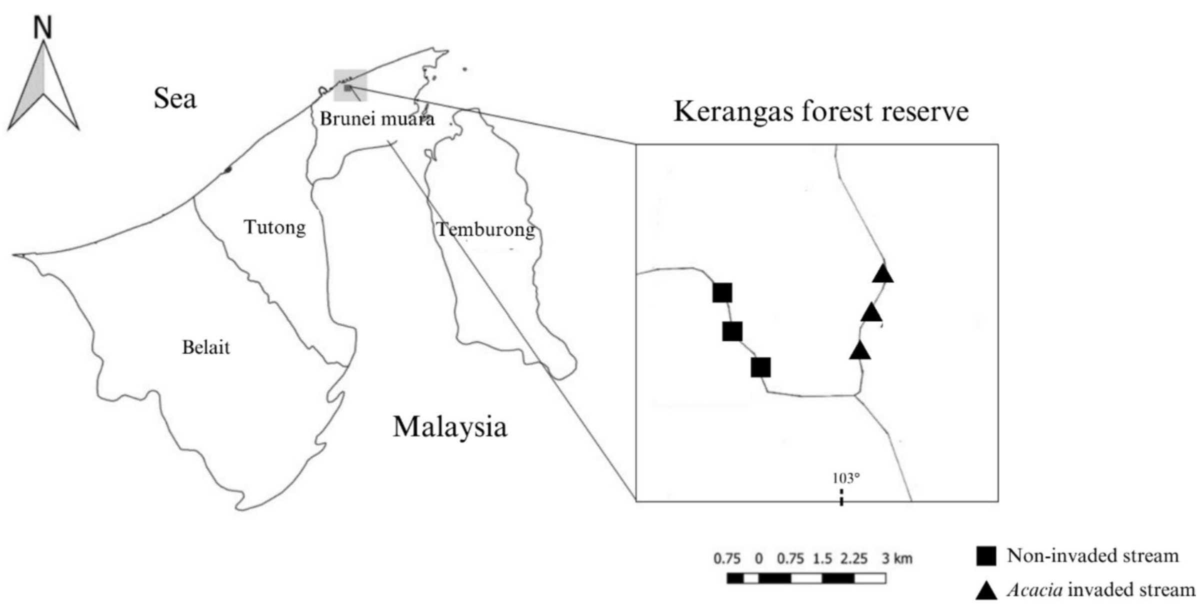


**Fig. 1** Locations of the study sites in the Kerangas Forest Reserve, Brunei Darussalam, Northwest Borneo. The map shows three sampling stations (upstream, midstream, downstream) for both *Acacia*-invaded (IN) and non-invaded (NIN) streams. Stations are located along the riparian zone at distances relative to the forest edge (e.g., upstream at ~ 50 m, midstream at ~ 300 m, and downstream at ~ 600 m)

Water samples were collected using sterile polyethylene bottles monthly over 6 months ($n=6$) from each station (upstream, midstream, and downstream) in both *Acacia*-invaded (IN) and non-invaded (NIN) streams. At each station, three replicate samples were collected for each parameter and subsequently averaged to represent the station's water quality for that month. To preserve sample quality, the bottles were rinsed with the stream water prior to collection. The samples were then filtered through a 0.22-µm pore-size filter and stored at approximately 4 °C for further analysis within 24 h.

### In situ analysis

The measurements were conducted using the Mettler Toledo SevenGo Duo pro™ pH Multi-Probe Checker (Mettler Toledo, Switzerland). The parameters were recorded with the following units: pH (unitless), conductivity (µS/cm), salinity (PSU), and total dissolved solids [TDS] (mg/L) in situ. The device was calibrated before each use following the manufacturer's guidelines to ensure accurate measurements. The streams had depths ranging from 20 to 50 cm during the dry season, and measurements were taken at the surface, middle, and bottom to capture vertical variability in water properties. Measurements were taken directly at each station by immersing the probe at the designated depths until a stable reading was recorded. This method ensured consistency and accuracy across all sampling points.

### Laboratory analysis

#### *Phosphate, nitrate, ammonia, and nitrite*

The analytical methodologies employed to quantify the concentrations of various nutrient ions specifically phosphate ($PO_4$), nitrate ($NO_3$), ammonia ($NH_4$), and nitrite ($NO_2$) were rigorously applied using a Hach spectrophotometer (Model AP-903). The measurements were conducted with wavelengths of 620 nm for phosphate, nitrate, and ammonia, and 405 nm for nitrite, as recommended by the manufacturer for optimal accuracy with the reagents used and a scan speed of 20 mm/s.

### Statistical analysis

The statistical analyses were performed using Statistical Analysis System version 9.2 (SAS Corp, 2009). For water properties, mean values per plot within each depth were calculated and used in an unpaired *t*-test to determine differences between *Acacia*-invaded ($n=3$ stations) and non-invaded stream ($n=3$ stations). We checked all the data for homogeneity of variances and normality of residuals, but we found no evidence of these assumptions being violated. Prior to analysis, the percentage data were transformed using the arcsine-square root method (Ahrens et al., 1990). A Pearson correlation analysis was conducted to determine the relationship between water quality and *Acacia* invasion in Kerangas forest stream independent of sites. The data were then subjected to principal component analysis (PCA) to visualize distinctions between sites based on a set of variables and to identify which variables accounted for these distinctions, using R 3.5.1 software (R Development Core Team, 2018).

## Results

### Water properties variation in the Kerangas stream due to *Acacia* invasion

Using a paired sample *t*-test, we found that the water samples from the *Acacia*-invaded (IN) and non-invaded (NIN) Kerangas streams varied significantly over the sampling period from September 2015 to February 2016, except for ammonium in water ($NH_4^+$). Significant differences were observed for pH ($t=5.62$, df $=5$, $p<0.01$), nitrate ($t=4.87$, df $=5$, $p<0.01$), and phosphate ($t=4.32$, df $=5$, $p<0.01$). The result showed that the pH of all water samples was higher in the *Acacia*-invaded stream than in the non-invaded stream, consistently over the entire period of observation. The measurement of pH showed that the pH of the water with IN was 5.68 higher (difference $=1.85$, $p<0.0001$) than the pH in NIN (4.01) (Table 1).

However, a different pattern emerged for the variables water conductivity, salinity, and total suspended solids, where measurements of water samples from NIN stream were significantly higher ($p<0.05$) than IN stream. The results presented for water conductivity,

**Table 1** Temporal distribution of water properties collected at different sampling times (September, October, November, and December 2015 and January and February 2016) of stream to Kerangas forest: non-invaded [NIN] (without parenthesis) and *Acacia*-invaded [IN] (with parenthesis) $n=6$. Unpaired *t*-test was conducted for differences in means between sites. Bold numbers represent significant at $*p<0.05$, $**p<0.01$, $***p<0.001$. Abbreviations: *pH* pH of water, *Cond.* water conductivity, *Salt.* salinity, *TDS* total dissolve solid, $NO_3^-$ nitrate in water, $NH_4^+$ ammonium in water, and $PO_4^{3-}$ phosphate in water

| | Sampling period (month) | | | | | | |
|---|---|---|---|---|---|---|---|
| | Sep 2015 | Oct 2015 | Nov 2015 | Dec 2015 | Jan 2016 | Feb 2016 | Overall |
| pH | 3.73 ± 0.04<br>(5.54 ± 0.14) | 3.86 ± 0.08<br>(4.99 ± 0.25) | 4.46 ± 0.31<br>(5.80 ± 0.05) | 4.24 ± 0.17<br>(5.91 ± 0.19) | 4.03 ± 0.14<br>(5.87 ± 0.24) | 3.78 ± 0.08<br>(5.97 ± 0.05) | 4.01 ± 0.31<br>(5.68 ± 0.38) |
| *t*-value | −22.93 | −10.56 | −8.93 | −9.08 | −8.25 | −29.19 | −16.99 |
| *p* | **0.002** | **0.009** | **0.012** | **0.012** | **0.014** | **0.001** | **< .0001** |
| Cond. (μS cm$^{-1}$) | 11.71 ± 1.00<br>(2.89 ± 0.16) | 10.49 ± 1.01<br>(2.36 ± 0.15) | 6.82 ± 0.52<br>(2.71 ± 0.13) | 6.29 ± 0.66<br>(2.51 ± 0.08) | 6.58 ± 0.19<br>(3.17 ± 0.11) | 9.62 ± 1.53<br>(3.11 ± 0.42) | 8.59 ± 2.40<br>(2.79 ± 0.35) |
| *t*-value | 13.95 | 13.29 | 11.48 | 10.85 | 22.15 | 7.58 | 10.05 |
| *p* | **0.005** | **0.006** | **0.008** | **0.008** | **0.002** | **0.02** | **< .0001** |
| Salt. (psu) | 0.013 ± 0.001<br>(0.010 ± 0.001) | 0.012 ± 0.001<br>(0.009 ± 0.001) | 0.012 ± 0.001<br>(0.010 ± 0.001) | 0.012 ± 0.001<br>(0.010 ± 0.001) | 0.011 ± 0.001<br>(0.010 ± 0.001) | 0.012 ± 0.001<br>(0.010 ± 0.001) | 0.012 ± 0.001<br>(0.010 ± 0.000) |
| *t*-value | 11.00 | 8.60 | 5.00 | 5.00 | 4.00 | 8.00 | 10.80 |
| *p* | **0.01** | **0.02** | **0.04** | **0.04** | 0.06 | **0.02** | **< .0001** |
| TDS (mg L$^{-1}$) | 7.49 ± 0.64<br>(1.85 ± 0.10) | 6.71 ± 0.65<br>(1.51 ± 0.10) | 4.37 ± 0.34<br>(1.74 ± 0.01) | 4.02 ± 0.42<br>(1.61 ± 0.05) | 4.21 ± 0.67<br>(2.03 ± 0.07) | 6.16 ± 0.98<br>(1.87 ± 0.08) | 5.49 ± 1.53<br>(1.77 ± 0.19) |
| *t*-value | 13.91 | 13.28 | 11.42 | 10.79 | 5.54 | 7.74 | 10.06 |
| *p* | **0.005** | **0.006** | **0.008** | **0.009** | **0.03** | **0.02** | **< .0001** |
| $NO_3^-$ (mg L$^{-1}$) | 0.27 ± 0.06<br>(2.60 ± 0.17) | 0.73 ± 0.06<br>(2.60 ± 0.56) | 1.23 ± 0.06<br>(3.78 ± 0.46) | 1.10 ± 0.10<br>(3.33 ± 0.51) | 1.43 ± 0.15<br>(3.50 ± 0.40) | 1.63 ± 0.47<br>(7.03 ± 0.68) | 1.07 ± 0.50<br>(3.81 ± 1.61) |
| *t*-value | −26.46 | −5.69 | −10.86 | −6.60 | −9.45 | −11.78 | −8.82 |
| *p* | **0.001** | **0.03** | **0.008** | **0.02** | **0.01** | **0.007** | **< .0001** |
| $NH_4^+$ (mg L$^{-1}$) | 0.013 ± 0.006<br>(0.013 ± 0.006) | 0.013 ± 0.006<br>(0.013 ± 0.006) | 0.023 ± 0.015<br>(0.013 ± 0.006) | 0.017 ± 0.012<br>(0.013 ± 0.006) | 0.013 ± 0.006<br>(0.027 ± 0.021) | 0.020 ± 0.017<br>(0.017 ± 0.011) | 0.017 ± 0.010<br>(0.016 ± 0.010) |
| *t*-value | 0.00 | 0.00 | 0.87 | 1.00 | −0.92 | 0.23 | 0.14 |
| *p* | 1.00 | 1.00 | 0.48 | 0.42 | 0.46 | 0.84 | 0.89 |
| $PO_4^{3-}$ (mg L$^{-1}$) | 0.60 ± 0.10<br>(2.93 ± 0.75) | 0.80 ± 0.10<br>(2.90 ± 0.79) | 1.23 ± 0.25<br>(3.77 ± 0.46) | 1.10 ± 0.10<br>(3.33 ± 0.51) | 1.43 ± 0.15<br>(3.17 ± 0.70) | 1.46 ± 0.47<br>(7.03 ± 0.68) | 1.10 ± 0.38<br>(3.85 ± 1.59) |
| *t*-value | −4.87 | −4.17 | −6.45 | −6.60 | −3.74 | −9.58 | −7.89 |
| *p* | **0.04** | **0.04** | **0.02** | **0.02** | **0.04** | **0.01** | **< .0001** |

salinity, and total dissolved solids in the NIN stream showed significant differences at $p<0.0001$ for all sampling periods compared to the IN stream (diff = 5.80 μS cm$^{-1}$, 0.002 psu, and 3.72 mg L$^{-1}$) (Table 1). The other water variables such as nitrate ($NO_3^-$) and phosphate ($PO_4^{3-}$) concentration in the water were higher in the water of the IN stream than those of the NIN stream (difference = 2.64 and 2.75 mg L$^{-1}$, respectively) (Table 1).

## Relevant correlation between the water properties of the Kerangas water

Using correlation analysis, we determined the relationship (positive or negative relationship) and its significance for water properties in the *Acacia*-invaded (IN) and non-invaded (NIN) Kerangas stream. For the NIN stream, the pH of the water was found to be negatively correlated with water conductivity, salinity,

**Table 2** Pearson's correlation coefficient (r) analysis among water properties of non-invaded (NIN) and *Acacia*-invaded (IN) sites of stream in Kerangas forest ($n=18$). *Correlation is significant were bold at *$p<0.05$, **$p<0.01$, ***$p<0.001$. Abbreviations: *pH* pH of water, *Cond.* water conductivity, *Salt.* salinity, *TDS* total dissolve solid, $NO_3^-$ nitrate in water, $NH_4^+$ ammonium in water, and $PO_4^{3-}$ phosphate in water

| | *Acacia* non-invaded | | | | | | |
|---|---|---|---|---|---|---|---|
| | pH | Cond | Salt | TDS | Nit | Ammo | Phos |
| pH | 1.00 | | | | | | |
| Cond | **−0.80*** ** | | | | | | |
| Salt | **−0.78** ** | **0.95*** ** | | | | | |
| TDS | **−0.80*** ** | **0.98*** ** | **0.95*** ** | | | | |
| $NO_3^-$ | 0.27 | **−0.50*** | **−0.49*** | **−0.50*** | | | |
| $NH_4^+$ | 0.13 | −0.26 | −0.15 | −0.26 | 0.02 | | |
| $PO_4^{3-}$ | 0.37 | **−0.54*** | **−0.54*** | **−0.54*** | **0.91*** ** | −0.12 | 1.00 |
| | *Acacia* invaded | | | | | | |
| pH | 1.00 | | | | | | |
| Cond | **0.49*** | | | | | | |
| Salt | 0.02 | −0.15 | | | | | |
| TDS | **0.49*** | **0.94*** ** | −0.14 | | | | |
| $NO_3^-$ | **0.50*** | 0.42 | −0.08 | 0.32 | | | |
| $NH_4^+$ | 0.32 | 0.41 | −0.20 | 0.34 | −0.06 | | |
| $PO_4^{3-}$ | 0.39 | 0.38 | −0.09 | 0.26 | **0.96*** ** | −0.08 | 1.00 |

and total dissolved solids (Table 2). However, in the IN stream, there was a significant positive correlation between water pH and water conductivity, total dissolved solids, and nitrate.

Based on these results, we found that a higher correlation coefficient of nitrate ($r=0.05$, $p<0.05$ [significant]) could be one of the factors for a higher pH of the water in the IN stream. The results showed a significant positive correlation between water conductivity and total dissolved solids ($r=0.98$ and 0.94, $p<0.01$ [significant], respectively) and phosphate and nitrate ($r=0.91$ and 0.96, $p<0.001$ [significant], respectively) (Table 2). In addition, the results also showed that phosphate in water was significantly negatively correlated with water conductivity, salinity, and total dissolved solids ($r=-0.54$).

## Influential variables of water properties of Kerangas water streams

Using principal component analysis (PCA), we determined the most influential variables of the seven water properties of *Acacia*-invaded (IN) and non-invaded (NIN) Kerangas stream. The result shows that the first two axes accounted for 61.98% of the total variation (Table 3). PC1 represented a gradient where the concentration of pH, nitrate, and phosphate in the water increased, while conductivity, salinity, and total dissolved solids decreased. PC2 represented a separate gradient where ammonium levels in the water decreased (Table 3). A biplot of the PC1 and PC2 axes showed that *Acacia*-invaded (IN) and non-invaded (NIN) Kerangas stream were distributed differently in the ordination axes (Fig. 2). The pH,

**Table 3** Principal component analysis (PCA) of seven water variables for non-invaded (NIN) and *Acacia*-invaded (IN) sites of stream of Kerangas forest. Percentage total variation explained by each principal component axis and loadings of each water properties for the first three principal component axes were presented. Bold numbers represent moderate and strong loading of PCA (principal component analysis). Abbreviations: *pH* pH of water, *Cond.* water conductivity, *Salt.* salinity, *TDS* total dissolve solid, $NO_3^-$ nitrate in water, $NH_4^+$ ammonium in water, and $PO_4^{3-}$ phosphate in water

| Parameters | Principal component axis | |
|---|---|---|
| | 1 | 2 |
| % total variation explained | 51.62 | 10.36 |
| Cumulative % variation explained | 51.62 | 61.98 |
| Loadings of water properties | | |
| pH | **0.95** | −0.06 |
| Cond | **−0.95** | −0.11 |
| Salt | **−0.96** | −0.08 |
| TDS | **−0.95** | −0.11 |
| $NO_3^-$ | **0.88** | −0.16 |
| $NH_4^+$ | −0.01 | **−0.97** |
| $PO_4^{3-}$ | **0.88** | −0.18 |

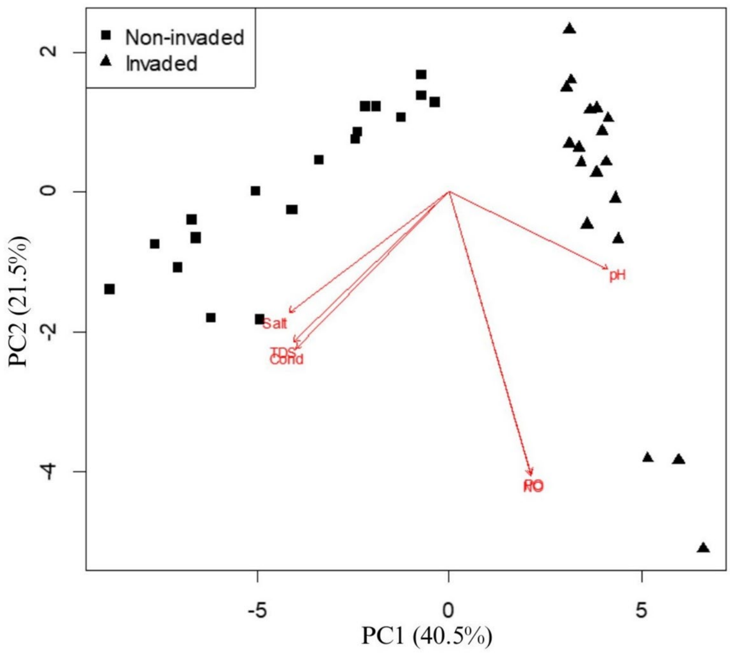


**Fig. 2** Biplot of principal component (PC) axes 1 and 2 from principal component analysis (PCA) of six water variables the two stream types: non-invaded *Acacia* (square) and invaded *Acacia* (triangle) sites of stream of Kerangas forest. Abbreviations: pH, pH of water; Cond., water conductivity; Salt., salinity; TDS, total dissolve solid; $NO_3^-$, nitrate in water; and $PO_4^{3-}$, phosphate in water

phosphate, and nitrate levels in the water influenced the IN stream. In the NIN stream, conductivity, salinity, and total dissolved substances were the primary influencing factors.

## Discussions

### Variation in water properties in Kerangas stream due to *Acacia* invasion

In our study, the pH of water in both *Acacia*-invaded (IN) and non-invaded (NIN) streams ranged from 3.73 to 5.97, reflecting acidic conditions typical of peatlands with high organic content. These findings align with Zainorabidin and Mohamad (2016), who reported peatland water pH below 5 due to humic acids from decaying wood materials. Similarly, Kerangas soils are highly acidic (pH 2.9–4) with significant humus depth, as observed in Central Kalimantan, Indonesia (Miyamoto et al., 2003). During runoff, soluble humic acids leach into streams, lowering pH levels depending on water flow and decomposition rates (Tungsudjawong et al., 2017). Our results have also shown that the pH of the water stream is higher in IN stream than in NIN stream. The higher pH in the *Acacia*-invaded (IN) stream compared to the non-invaded (NIN) stream may be attributed to the reduced input of humic acids due to lower soil organic matter. *Acacia* spp. produce high-lignin leaves, which decompose less efficiently, resulting in a decreased production of humic acids that typically lower soil and water pH (Pereira et al., 2021). This reduction in organic acids diminishes acidification in the stream, while lower microbial activity, particularly processes like nitrification, also contributes to fewer acidifying by-products. Additionally, the reduced leaching of organic acids increases the buffering capacity of the water, further contributing to the observed higher pH levels. Although *Acacia* spp. produce high biomass, the quality of the biomass is crucial in determining its contribution to organic matter in the soil and streams. *Acacia* leaves, such as those of *Acacia auriculiformis*, are high in lignin, which slows decomposition (Ganesh et al., 2009; Jamaludheen & Kumar, 1999). As a result, the breakdown of this biomass into humic substances is limited, reducing the availability of organic acids in the soil and streams despite high biomass production. This slower decomposition affects nutrient cycling and the pH of stream water, as fewer acidifying compounds are released.

In general, the water conductivity in our *Acacia*-invaded stream, which did not differ significantly from that of an intact heath stream, ranged from 2.5 to 4.0 µS cm$^{-1}$. This range is lower compared to the Maliau Basin Conservation Area, Sabah, Malaysia, where conductivity ranged from 23 to 42 µS cm$^{-1}$ (Harun et al., 2010). This difference may be due to variations in soil composition, organic matter, or geological factors between these heath forest ecosystems. Generally, the conductivity of water in peat and Kerangas water channels is lower due to the high content of organic matter, which includes dissolved and suspended matter. For instance, the total dissolved solids in the Kerangas forest in Kalimantan are lower compared to those in the Dipterocarp Forest (Ponziani et al., 2011). The lower conductivity of water in peat and Kerangas water channels can be attributed to the high levels of organic matter, which are non-electrolytes (high buffering capacity) and do not conduct electricity (Kingsbury et al., 2017). In our study, the water conductivity in the *Acacia*-invaded (IN) stream did not differ significantly from the non-invaded (NIN) stream. As Bhateria and Jain (2016) stated, the conductivity of water depends on its acidity and the concentration of ions in the solution. Our results support this, showing a significant negative correlation between pH and conductivity in the non-invaded (NIN) stream ($r = -0.68$, $p < 0.05$), indicating that higher acidity (lower pH) increases the mobility of ions, leading to higher conductivity. Conversely, in the *Acacia*-invaded (IN) stream, the relationship between pH and conductivity was positive ($r = 0.45$, $p < 0.05$), reflecting altered ionic interactions likely influenced by changes in water chemistry due to *Acacia* invasion.

The slight increase in salinity (0.002 psu) and TDS (3.72 mg/L) in the NIN stream compared to the IN stream is minimal and falls well within safety limits for freshwater ecosystems which are TDS and salinity about g/L (1000 mg/L) and 0.5 psu, respectively (Knight et al., 2019). While the current differences are not ecologically concerning, they highlight the potential for long-term changes in water quality due to factors such as riparian vegetation and land use, necessitating continued monitoring. The sites invaded by *Acacias* had higher salinity, which could be due to the tannin content of the tree bark and leaves. This could affect water quality by increasing the concentration of dissolved solids and affecting plant growth (Elfeel & Bakhashwain, 2012). The concentrations of nitrate ($NO_3^-$) and phosphate ($PO_4^{3-}$) in the water were higher in the *Acacia*-invaded areas compared to the non-invaded areas. This can be attributed to the combination of high biomass and litter deposition from *Acacia*, which, despite slower decomposition due to high lignin content, leads to a gradual accumulation of nutrients in the soil and increased leaching into streams over time (Yannelli et al., 2019). The higher nitrate and phosphate levels in the water can lead to increased activity of aerobic and anaerobic microorganisms such as algae, which ultimately affect water quality (Johnston, 1991).

## Correlation water properties of Kerangas stream due to *Acacia* invasion

The correlation analysis indicated that *Acacia* invasion in the Kerangas forest influences water chemistry, particularly increasing pH, salinity, conductivity, nitrate, and phosphate levels. While our study observed significant nutrient differences between *Acacia*-invaded (IN) and non-invaded (NIN) streams, as shown in Table 1, the magnitude of these changes appears less pronounced compared to prior studies in more degraded ecosystems (Marchante et al., 2008; Pereira & Ferreira, 2020). Our findings highlight the need for targeted management strategies focusing on mitigating nutrient leaching and alterations in water chemistry caused by the *Acacia* invasion. For example, controlling *Acacia* spread in riparian zones, where nutrient inputs directly influence water quality, may help reduce the observed increases in nitrate and phosphate levels. Additionally, promoting the restoration of native vegetation could counterbalance nutrient cycling disruptions and improve water quality. These insights contribute to a more nuanced understanding of how invasive species like *Acacia* affect forest water ecosystems and provide a basis for informed conservation and management efforts.

## Influential variables of water properties of Kerangas water canal stream due to *Acacia* invasion

There are some variables that could have an impact on the water quality of the Kerangas stream. The first PCA axis (PC1 and PC2) accounted for 60% of the total variance and explained variables such as water pH, nitrate, and phosphate. The second PCA axis (PC2) accounted for 36% of the total variance and explained only the variables ammonium in the water.

The PCA results show that the most influential variables on water quality are pH, nitrate, and phosphate. This could be because *Acacia* spp. can alter nutrient cycling and eventually increase nutrient concentrations in groundwater, as reported by Chamier et al. (2012). Considering these results, it is important to consider the impact of *Acacia* invasion on water quality when planning management strategies for the Kerangas stream. For example, consistent measurements of pH and nutrient content provide valuable data for monitoring the impact of *Acacia* invasion on water quality. This information can guide management strategies, such as targeted removal of *Acacia* from riparian zones or replanting native species to restore nutrient cycling and improve water quality. These results emphasize the necessity of targeted management strategies to control *Acacia* invasion, as its presence disrupts nutrient cycling and degrades water quality in Kerangas forest streams. Implementing proactive measures to mitigate *Acacia* proliferation, coupled with continuous monitoring, can safeguard both terrestrial and aquatic ecosystem health. Furthermore, conservation strategies must integrate stakeholder education to ensure sustainable practices and foster collective action against the spread of invasive species.

### Implication management of the study

The findings of this study emphasize the need for targeted management strategies to mitigate the ecological impacts of *Acacia* invasion on Kerangas forest streams. Elevated pH, nitrate, and phosphate levels in invaded streams suggest potential risks such as eutrophication, which can disrupt aquatic ecosystems and harm native biodiversity. These water quality changes, although still within safety limits for some freshwater ecosystems, highlight the long-term risks of nutrient enrichment and altered water chemistry. While the study focused on Kerangas forest streams, the observed impacts of *Acacia* invasion on water quality are relevant to other sensitive ecosystems globally, particularly in regions with nutrient-poor soils or high biodiversity, such as heath forests, tropical wetlands, and riparian zones. Similar patterns of increased nutrient loading and altered water chemistry have been reported in other areas where invasive plants dominate, suggesting that these findings can provide broader insights into managing invasive species in comparable ecosystems.

Effective management should focus on controlling *Acacia* proliferation in riparian zones through regular monitoring and removal programs, while promoting the restoration of native vegetation to restore natural nutrient cycling. Restoration strategies tested in the Kerangas forest, such as promoting native plant growth and removing invasive species, could be adapted to other ecosystems to curb nutrient enrichment and maintain ecological balance. Additionally, stakeholder engagement and education initiatives are crucial to ensure sustainable management practices and foster collaboration among conservationists, local communities, and policymakers to protect ecosystems beyond the Kerangas forest from further degradation. This study underscores the global importance of addressing invasive species' impacts on sensitive ecosystems, providing a foundation for management practices across tropical and subtropical regions.

## Conclusions

This study described the significant impacts of the *Acacia* invasion on the water quality of Kerangas forest streams. It was found that the presence of *Acacias* significantly increased the pH, nitrate, and phosphate levels of the water. The pH of the invaded streams ranged from 5.68 to 5.97, which is higher than the optimal acidic range of 4.0 to 5.5 typically observed in pristine peatland streams. Similarly, nitrate concentrations (4.64 mg/L) and phosphate concentrations (3.75 mg/L) in the invaded streams exceeded the thresholds considered safe for freshwater ecosystems (1.0 mg/L for nitrate and 0.1 mg/L for phosphate), indicating significant nutrient enrichment and a disruption of water chemistry. In addition, the study found an increase in nutrient levels in the stream, likely triggered by the *Acacia* invasion, which could pose significant challenges to native aquatic life such as eutrophication. Comprehensive analysis underscores the negative water quality impacts caused by the invasive *Acacia*, highlighting the need for effective restoration strategies. Eradication or at least control of the invasive *Acacia* population is a critical step toward improving water quality. There is also an obvious need for education programs for residents and relevant stakeholders that focus on water quality conservation and best management practices. These educational efforts should aim to foster a deep understanding and appreciation of the intrinsic value of this indispensable natural resource, thus spurring community-driven initiatives to protect the water quality of Kerangas forest from further invasion degradation.

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**Author contribution** [MHI]: Conceptualized the research, designed the methodology, performed experiments, analyzed the data, wrote the original draft, and reviewed & edited the manuscript. [SJ]: Assisted with the methodology, conducted field sampling, assisted with data analysis, and reviewed & edited the manuscript.

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**Data availability** No datasets were generated or analysed during the current study.

**Declarations**

**Conflict of interest** The authors declare no competing interests.

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