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Assessing mangrove density and distribution related to petroleum hydrocarbon contamination in Segara Anakan Lagoon, Cilacap, Indonesia

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Abstract. *Hilmi E, Sanjayasari D, Pereira O, Hartoyo, Haryono FED, Cahyo TN, Amron A, Junaidi T, Fikriyya N, Yusof KMKK. 2025. Assessing mangrove density and distribution related to petroleum hydrocarbon contamination in Segara Anakan Lagoon, Cilacap, Indonesia. Biodiversitas 26: 6074-6088.* Total Petroleum Hydrocarbons (TPHs) are hazardous oil pollutant that has negative impact on mangrove ecosystem. In contaminated area, mangrove species might develop mechanism to reduce, accumulate, and transfer TPHs contaminants, yet this might affect their growth. This study aimed to analyze the relationship between TPHs with mangrove density and distribution based on the varying levels of TPHs in Segara Anakan Lagoon, Cilacap, Central Java, Indonesia. The research employed principal component analysis, utilizing the variables of water and soil TPHs, leaf TPHs, stem TPHs, root TPHs, number of species, species density, temperature, water salinity, pH, and TDS across seven research stations. The results showed that mangrove density ranged from 603-1295 trees ha^{-1} (low density). The potential TPHs were between 0.01-0.06% in water and 2.5-8.34% in sediment. The correlation between TPHs in water and the number of species was 0.844 (strong correlation), and with mangrove density was -0.083 (weak correlation). The correlation between TPHs in sediment and the number of species was 0.852 (strong correlation) and with density was -0.248 (weak correlation). The clustering analysis of mangrove stations revealed four clusters representing varying levels of contaminated areas. In addition, the clustering analysis of mangrove species revealed four groups representing different adaptation. This study found several dominant species which have high ability to live and grow in the TPHs contaminant areas including *Sonneratia caseolaris, Ceriops tagal, Rhizophora apiculata, Bruguiera gymnorhiza, Xylocarpus granatum, Avicennia marina, Rhizophora stylosa,* and *Rhizophora mucronata*. Such species are recommended to support mangrove rehabilitation in TPHs contaminated areas.

Keywords: Ecological clustering, mangrove adaptation, PCA, petroleum hydrocarbon, species density

INTRODUCTION

The petroleum refining industry is crucial for energy and chemicals but significantly contributes to environmental pollution (Grobelak et al. 2020; Al Hoqani et al. 2025). Total Petroleum Hydrocarbons (TPHs) are vital energy sources in refining and petrochemical sectors (Al-Haddad et al. 2022; Al Hoqani et al. 2025; Ishola et al. 2025). These contaminants are released during crude oil production, exploration, and transportation (Al-Haddad et al. 2022). However, excessive TPH contamination leads to disasters in marine, lagoon, and coastal ecosystems, affecting aquatic organisms' health (Ahmadkalaei et al. 2021; Taheri et al. 2022). Onyegeme-Okerenta et al. (2022) reported TPH levels from 14 factories along the Buguma River at 90.60 ± 5.39 mg kg^{-1}, impacting both aquatic and irrigation ecosystems (> 5 mg/L). Biogeochemical transformation is necessary to mitigate TPH contaminants' impact (Resmi et al. 2016).

Total Petroleum Hydrocarbons (TPHs) are persistent organic pollutants, consisting of aromatic hydrocarbons with two or more connected benzene rings (Yan et al. 2023). TPHs undergo biological and chemical processes that affect the stability of coastal marine ecosystems, including mangroves, estuaries, and salt marshes (Abbasi and Keshavarzi 2019; Wei et al. 2022). In both water and sediment, TPHs pose a growing toxic threat to aquatic life and ecosystems (Akinola et al. 2019; Mirjani et al. 2021; Wei et al. 2022; Iheme et al. 2025). Evaluating their impact on soil and microecosystems is essential for assessing habitat degradation (Raja et al. 2022; Zhang et al. 2023; Wu et al. 2025).

Total Petroleum Hydrocarbons (TPHs), as major toxic pollutants, significantly impact human health and the environment, including mangrove ecosystems (Taheri et al. 2022; Moses et al. 2023). TPHs induce stress in mangroves, causing damage, inhibited growth, and higher mortality rates. Studies have shown that the absorption of aromatic and aliphatic fractions causes stress in Avicennia germinans, Rhizophora mangle, and other mangrove species (Al-Hadi et al. 2014; Ameen et al. 2016; Wu et al. 2025). To mitigate the effects of TPH contaminants, oil spills, and heavy metals, mangroves must exhibit strong adaptability (Ameen et al. 2016; Abbasi and Keshavarzi 2019). Their adaptation in polluted ecosystems can be enhanced through strategies such as clustering, affinity, growth, and regeneration (Cahyo et al. 2024; Hilmi et al. 2024).

The Eastern Segara Anakan Lagoon (E-SAL) in Cilacap, Central Java, Indonesia, hosts industries such as oil refineries, cement plants, and a hydroelectric power plant, all of which release waste, including petroleum hydrocarbons. The presence of mangroves in E-SAL is expected to help mitigate the impacts of these hydrocarbons, as the lagoon acts as a waste disposal site for the nearby petroleum industry. Syakti et al. (2013a, b) report that petroleum hydrocarbons in E-SAL trigger biological responses from algae, phytoplankton, zooplankton, mangrove debris, vegetation, and microbes, influencing ecological interactions between microbes and macro-organisms (Rigonato et al. 2018).

Mangrove density reflects the prevalence and dominance of species in an ecosystem (Sari and Rosalina 2016; Hilmi et al. 2021b, c; Murniasih et al. 2022), indicating species affinity, distribution, and clustering. It also reflects ecosystem stability, categorized into rare, moderate, dense, and very dense classes (Hilmi et al. 2019; Azman et al. 2021). However, mangrove density can decrease due to factors like TPH contamination (Moreira et al. 2011; Cochard 2017). TPHs significantly impact mangrove density, survival, distribution, and species adaptation (Ameen et al. 2016; Wei et al. 2022).

Principal Component Analysis (PCA) is a statistical method used to reduce dimensionality by transforming datasets with correlated variables into uncorrelated ones (Cooray et al. 2021; Zhong et al. 2023). In the context of TPH-mangrove interactions, PCA helps examine correlations between variables such as mangrove density, species density, water and soil TPHs, TPHs in roots, leaves, and stems, species count, salinity, pH, and TDS. PCA provides a correlation matrix, eigenvalues, variability, cumulative distribution, and box plots of mangrove species distribution in TPH-affected areas (Khudur and Ball 2018; Taheri et al. 2022; Moses et al. 2023). It offers insights into ecological monitoring by assessing potential mangrove density and their adaptive responses to TPH contamination (Rigonato et al. 2018).

TPHs affect various aspects of mangrove ecosystems, including mangrove density, mortality, and species distribution. Some species adapt to reduce the impact of TPHs. Environmental factors like TPHs can also influence mangrove species clustering. This study aims to explore the correlations between mangrove and species density, TPHs in water, soil, roots, leaves, and stems, as well as species count, salinity, pH, and TDS in Segara Anakan Lagoon using principal component analysis. The findings are expected to enhance understanding of how TPHs impact mangrove growth, density, and ecosystem stability, including water and substrates.

MATERIALS AND METHODS

Study area and period

This research was conducted from June to July 2025 in Segara Anakan Lagoon (SAL), Cilacap, Central Java, Indonesia, as shown in Figure 1 and Table 1. Data were collected from seven sites: Sapuregel, East Plawangan, West Sleko, West Prenca, West Donan, West Pertamina, and Kalipanas River. These sites vary in mangrove density and dominant species (Hilmi 2018, et al. 2021c, et al. 2024) and have been affected by crude oil waste. Each site had three sampling plots, resulting in a total of 21 plots.

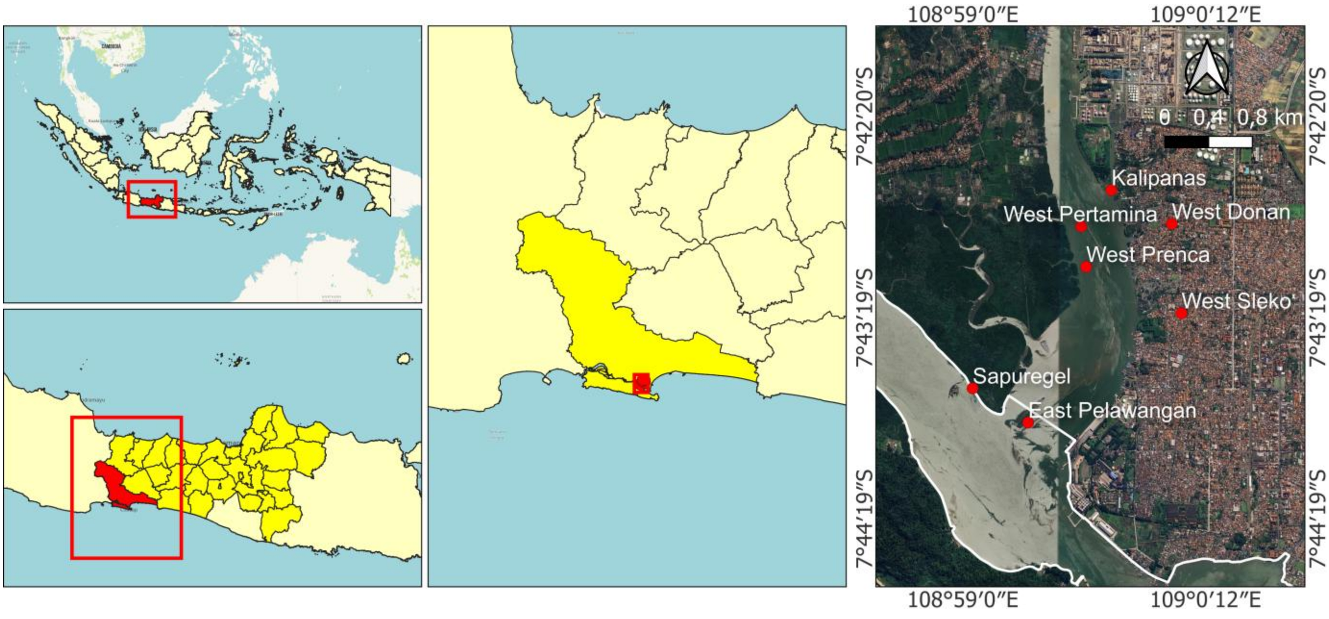

Figure 1. Map of study area in Segara Anakan Lagoon, Cilacap, Central Java Province, Indonesia

Table 1. Geographical coordinates of research sites in Segara Anakan Lagoon, Cilacap, Central Java, Indonesia

Location	Coordinate	
	Latitude (°S)	Longitude (°E)
Sapuregel	-7.72777	108.9841
East Pelawangan	-7.73058	108.9887
West Sleko	-7.72161	109.0014
West Prenca	-7.71780	108.9935
West Donan	-7.71428	109.0006
West Pertamina	-7.71449	108.9931
Kalipanas	-7.71151	108.9956

Table 2. Classification of mangrove density

Mangrove density class	Number of mangrove (trees ha^{-1})
Very low density	0-390
Low density	391-1610
Moderate	1611-2220
Good	2221-3137
Very high density	> 3137

Research procedures

Mangrove density

Transect method was employed to measure mangrove density (Kusmana and Septiarie 2014; Xiong et al. 2018; Domínguez-domínguez et al. 2019; Hilmi et al. 2019; Win et al. 2019; Ariyanto and Pringgenies 2024) as well as to document species occurrence and gather mangrove samples for TPHs analysis. Data on mangrove density was gathered from seven locations. Sampling plots were chosen according to TPH potential, which was determined by proximity to TPH contaminated zones. At each location, transect was created and sampling plots were established with size of each plot was 10 x 10m to record mangrove trees, i.e. mangrove plants with a diameter greater than 4 cm (Hilmi et al. 2019). Species dominance and mangrove density class were analysed using the method prescribed by Hilmi et al. (2019).

Mangrove density was calculated using the equation as follow:

$$\text{Mangrove density / species} = \frac{\text{Total trees / species (trees)}}{\text{Area (ha)}}$$

Mangrove density was divided into 5 classes following Hilmi et al. (2019) as presented in Table 2.

Total petroleum hydrocarbons

TPHs was analysed using spectrophotometric UV-Vis and GC-MS methods as outlined by the United States Environmental Protection Agency (US EPA) while adhering to gravimetric principles per Method 1664 of US EPA-821-R-98-002. The InfraCal TPH Analyzer model HATR-T2 and CVH were used to evaluate TPH content, measuring solvent extracts (hydrocarbons or fats and oils), water or wastewater, and utilizing n-hexane as the extraction agent. The sampling phases are described as follow. First, the vegetation was sampled as the preliminary step for preparing the roots, stems, and leaves. Stem and root samples were sliced into tiny size and then crushed until they became smooth. Leaf samples were crushed in a blender. A sample of up to 0.1 grams from stems, leaves, and roots was collected and put in 40 mL vial bottles. TPHs concentration was analysed using the InfraCal TPH Analyzer. Second, the sediment was sampled up to 0.1 gram and was stored in a 40 mL vial bottle. Next, the sediment was mixed with Na_2SO_4 and utilized a spatula to separate the lumps. TPHs levels was analysed using the InfraCal TPH Analyzer. Third, water samples were analysed directly, utilizing the InfraCal TPH Analyzer as well. Fourth, the water was then placed into the separatory funnel for further analysis. The water samples were modified to make the pH below 2 by incorporating 3 to 5 drops of hydrochloric acid or sulfuric acid. One-tenth of the sample volume of solvent was used to cleanse the interior of the bottle and cap (for a 177 mL test bottle, to facilitate the collection of 140 mL of water sample, subsequently add 14 mL of water solvent) (Abbasi and Keshavarzi 2019; Al-Haddad et al. 2022; Al Hoqani et al. 2025; Ishola et al. 2025). Fifth, after sample preparation, solvent was added with amount measured by the gram weight of the root, stem, and leaf. Once the samples were prepared, the measured solvent was incorporated based on the gram weight of the root, stem, and leaf samples, which was approximately 11.2 grams for each sample, along with 11.2 mL of solvent, to maintain an extraction ratio of 1:1. Next, this combination was mixed vigorously for two minutes and injected into a syringe equipped with a frit filter. Then, the plunger was placed into the nozzle to allow the solvent to flow through the filter into a clean container or straight into the cuvette. A piece of filter paper was positioned atop the filter funnel and one teaspoon of silica gel (70-150 mm) was added. The cuvette was added with the extract and inserted into the TPH analyser to produce the results of analysis.

Data analysis

The data were analysed using data tabulation, correlation analysis and Principal Component Analysis (PCA).

Data tabulation

The data tabulation used bar graph with standard deviation and average were inputted using Microsoft Excel.

Correlation analysis

Correlation analysis is a statistical method used to evaluate the relationship between two variables using the formula below (Larekeng et al. 2024):

$$r = \frac{\sum_{i=1}^{i} xy}{\sqrt{\left(\sum_{i=1}^{i} xi\right)^2 \left(\sum_{i=1}^{i} yi\right)^2}}$$

Where, r: Correlation score, $\sum_{i=1}^{i} xy$: Score total of x*y, $\sum_{i=1}^{i} xi$: Score total of x, $\sum_{i=1}^{i} yi$: Score total of y

Principal component analysis

Principal Component Analysis (PCA) was conducted to investigate the correlations among mangrove density, water TPHs, sediment, temperature, salinity, and pH levels. PCA relationship examination utilizes Pearson correlation coefficient (Zhong et al. 2023; Schemer et al. 2025). The Principal Component Analysis (PCA) phase encompasses (i) gathering extensive datasets of TPHs and environmental characteristics, (ii) condensing large datasets of TPHs and environmental features, and (iii) employing machine learning to examine dataset components. This principal component analysis utilized (i) linear regression for information compression, (ii) dimension reduction by eliminating low-information components and creating scatter plots, (iii) conducting geometric interpretation (variance explanation, data distribution, new axes). The PCA must also standardize and normalize data, compute covariance and correlation, find eigenvectors and eigenvalues (to determine the principal components), generate feature vectors (to choose important components), and rebuild data (to shift data along a new axis). The PCA results were interpreted by (i) generating a PCA plot using PC1 on the X-axis, PC2 on the Y-axis, and examining the connections among observations, (ii) assessing retained components (scree plot, cumulative explained variance, ideal number of components), (iii) analyzing loadings (direction of arrows), the length of arrows, and variables demonstrating high loadings, (iv) evaluating principal components starting with the first component analysis, followed by subsequent components and variance explanation. For PCA, this study employed XSTAT in Microsoft Excel.

The PCA stages in this study consisted of (i) measuring species density distribution through variables such as TPHs in water, TPHs in sediment, temperature, water salinity, pH, TDS, number of species, species density, and names of mangrove species, (ii) employing PCA of stations by variance of water TPHs, sediment TPHs, root TPHs, stem TPHs, leaf TPHs, temperature, water salinity, pH, TDS, number of species, species density, and names of mangrove stations, (iii) using correlation PCA with standardization n-1, (iv) adhering to the principle of not accepting missing data regarding TPH and mangrove density, (v) producing output with descriptive statistics, significance tests for correlation using the Kaiser-Meyer-Olkin measure, and Bartlett's sphericity test at 95%, yielding results including explained eigenvalues, factor loadings, variable factors, correlations, factor scores, and contributions as squared cosines, (vi) presenting observation charts with labels, color coding for a 95% confidence interval based on group data, while observation labels indicate specific locations.

The PCA analysis assumptions included (i) a priori criteria consisting of potential TPH for mangrove species (leaf, stem, root), potential TPH from substrate, water, water quality, mangrove species density, and location of TPH contaminants, (ii) eigenvalue criteria based on the elimination of variables with Eigenvalue < 1, (iii) variance criteria through percentage variance analysis.

RESULTS AND DISCUSSION

Mangrove density

Figure 2 shows mangrove density in East Segara Anakan Lagoon. Mangrove ecosystem in East Segara Anakan Lagoon was primarily composed of *Rhizophora apiculata* Blume (1340 trees ha^{-1}) followed by *Rhizophora stylosa* Griffith (1037 trees ha^{-1}), *Avicennia marina* (Forssk.) Vierh. (976 trees ha^{-1}), *Ceriops tagal* (Perr.) C.B.Rob. (602 trees ha^{-1}) and *Nypa fruticans* Wurmb (500 trees ha^{-1}). *Thespesia populnea* (L.) Sol. ex Corrêa, *Excoecaria agallocha* L., *Bruguiera sexangula* (Lour.) Poir., and *Xylocarpus moluccensis* (Lam.) M.Roem. were less abundant with densities ranging from 13 to 43 trees per hectare. The dominance of *R. apiculata* and *R. stylosa* is due to their ability to adapt with the environmental factors in E-SAL and is likely to able to mitigate the effects of petroleum hydrocarbon contaminants.

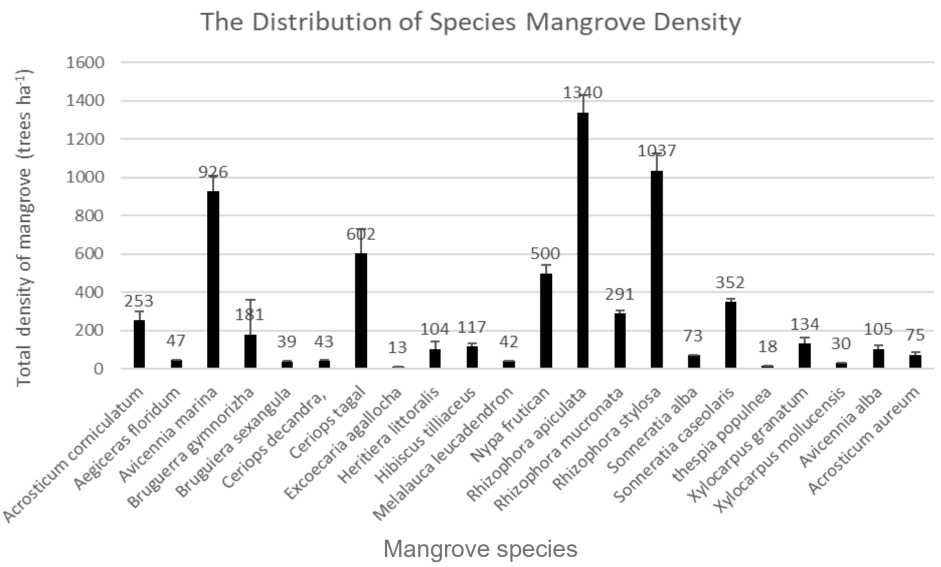

Figure 2. Mangrove density of each species in East Segara Anakan Lagoon, Cilacap, Central Java, Indonesia

Total Petroleum Hydrocarbons (TPHs) and mangrove density

Table 3 shows TPHs contamination and mangrove density. East Segara Anakan Lagoon had TPHs in water ranging from 0.01-0.06 % and in sediment/substrate from 2.0-8.34%. The dominant species in research stations in East Segara Anakan Lagoon included *C. tagal, R. apiculata, A. marina* and *R. stylosa* with density ranging from 603 trees/ha to 1295 trees/ha (low density of mangrove ecosystem).

Kalipanas River exhibited the highest levels of TPHs in both water (00.1-0.06%) and sediment/substrate (7.12-8.34%) due to its proximity to the petroleum waste disposal area. This indicates that TPHs are likely to have impacts on the low mangrove density in Kalipanas River, which was only 607 trees ha^{-1}.

Total petroleum hydrocarbons also impacted the adaptation of mangrove species (Table 4), which showed that *R. apiculata, C. tagal, R. stylosa, A. marina, Rhizophora mucronata* Lam. and *Sonneratia caseolaris* (L.) Engl. have high adaptation to mitigate the impacts of TPHs contamination in Segara Anakan. In Kalipanas, where it had the high levels of TPH, the site was dominated by *R. apiculata* and *A. marina*.

The correlation between Total Petroleum Hydrocarbons (TPHs) with mangrove density

Table 5 shows the correlation between mangrove density and Total Petroleum Hydrocarbons (TPHs). The result indicates that TPHs in sediment showed strong correlation with TPHs in water, yet the correlation both parameters with mangrove density remained weak (ranging from -0.083 to -0.248). Essentially, TPHs in both water and sediment adversely affect mangrove density.

Clustering analysis using Principal Component Analysis (PCA)

The cluster of research stations

TPHs in both water and sediment can affect mangrove density and the presence of particular mangrove as well as water salinity, pH levels and TDS. Principal Component Analysis (PCA) was employed to elucidate the clustering of research stations based on TPHs contamination. The result of PCA to cluster research stations is presented in Figure 3, Tables 7 and 8. Figure 3 shows four clusters of research station that indicate TPHs contamination, namely: West Pertamina and Kalipanas (first cluster), West Prenca and West Donan (second cluster), East Pelawangan dan West Sleko (third cluster) and Sapuregel (fourth cluster).

Table 6 shows that the density of mangroves had a negative correlation with TPHs in water (-0.083/weak correlation), TPHs in sediment (-0.247/weak correlation), temperature (-0.557/moderate correlation), and TDS (-0.354/weak correlation), while showing a positive correlation with water salinity (0.051/weak correlation) and pH (0.553/moderate correlation).

According to the eigenvalue presented in Table 8, the Sapuregel and East Pelawangan Stations exhibit negative eigenvalues, with the eigenvalue of F1 surpassing that of F2. The Kalipanas and West Prenca Stations exhibit positive eigenvalues and F1 is greater than F2. The West Sleko, West Donan, and West Pertamina Stations possess either negative or positive eigenvalues, with F2 exceeding F1. The first Principal Component (PC1) of the principal component analysis among mangrove stations explains 53.7% of the primary axis in the dataset, highlighting significant differences in environmental TPH levels in sediment and water. The components of the cluster in PC1 exhibit statistically contrasting loads, specifically the positive influence of sediment TPHs, species diversity, water TPHs, TDS, and temperature. The second principal component, while accounting for just 23.1% of the variance, adds an orthogonal dimension mainly shaped by pH and mangrove density as factors influencing the components in PC.

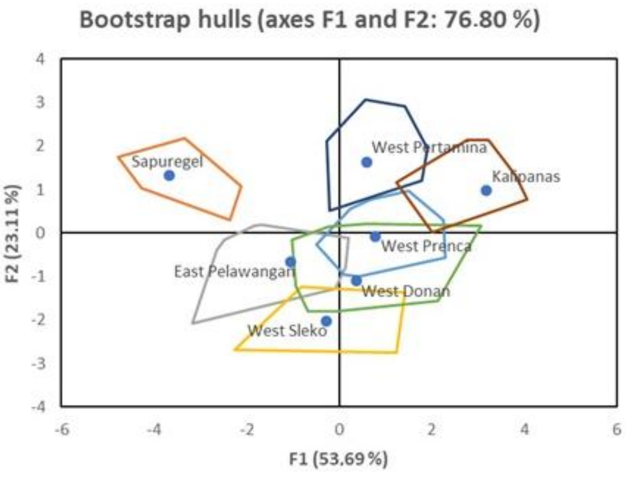

Figure 3. The cluster of research station in East Segara Anakan Lagoon, Cilacap, Central Java, Indonesia, clustered using principal component analysis

Table 3. Total Petroleum Hydrocarbons (TPHs) and mangrove density in each research station

Location	Water TPH (%)			Sediment TPH (%)			Mangrove density (trees ha^{-1})		Dominant species
	1	2	3	1	2	3	Density	Class	
Sapuregel	0.01	0.01	0.01	4.2	3.1	2.5	1092	Low density	*Ceriops tagal* and *Rhizophora apiculata*
East Plawangan	0.01	0.01	0.02	4.6	4.7	4.4	760	Low density	*Ceriops tagal* and *Rhizophora apiculata*
West Sleko	0.02	0.01	0.01	6.77	5.1	5.03	603	Low density	*Avicennia marina* and *Rhizophora apiculata*
West Prenca	0.02	0.01	0.03	5.9	5.5	5.6	942	Low density	*Rhizophora stylosa* and *Rhizophora apiculata*
West Donan	0.02	0.01	0.02	5.8	7.11	6.9	857	Low density	*Avicennia marina* and *Rhizophora apiculata*
West Pertamina	0.02	0.04	0.02	5.9	7	6.8	1295	Low density	*Rhizophora stylosa* and *Rhizophora apiculata*
Kalipanas River	0.01	0.06	0.04	7.32	7.12	8.34	607	Low density	*Rhizophora stylosa* and *Rhizophora apiculata*

Table 4. The distribution of mangrove species and its density in TPHs contaminant area

Stations (location)	TPH (%)		Mangrove species	Density (trees/ha)		
	Water	Sediment		Percent	Number	Total
Sapuregel	0.01	3.27	*Rhizophora apiculata* Blume	24%	262	1092
			Nypa fruticans Wurmb	15%	164	
			Aegiceras corniculatum (L.) Blanco	12%	131	
			Rhizophora stylosa Griffith	20%	218	
			Ceriops tagal (Perr.) C.B.Rob.	29%	317	
East Plawangan	0.01	4.57	*Sonneratia caseolaris* (L.) Engl.	8%	61	760
			Nypa fruticans Wurmb	11%	84	
			Rhizophora apiculata Blume	25%	190	
			Hibiscus tiliaceus L.	9%	68	
			Ceriops tagal (Perr.) C.B.Rob.	39%	296	
			Avicennia marina (Forssk.) Vierh.	8%	61	
West Sleko	0.01	5.63	*Rhizophora mucronata* Lam.	11%	66	603
			Avicennia marina (Forssk.) Vierh.	9%	54	
			Rhizophora apiculata Blume	14%	84	
			Nypa fruticans Wurmb	11%	66	
			Sonneratia caseolaris (L.) Engl.	12%	72	
			Rhizophora stylosa Griffith	18%	109	
			Avicennia marina (Forssk.) Vierh.	25%	151	
West Prenca	0.02	5.67	*Aegiceras corniculatum* (L.) Blanco	9%	85	942
			Bruguiera gymnorhiza (L.) Lam.	5%	47	
			Avicennia marina (Forssk.) Vierh.	13%	122	
			Rhizophora mucronata Lam.	9%	85	
			Rhizophora apiculata Blume	15%	141	
			Sonneratia caseolaris (L.) Engl.	9%	85	
			Rhizophora stylosa Griffith	16%	151	
			Nypa fruticans Wurmb	6%	57	
			Adiantum hispidulum Sw.	4%	38	
			Aegiceras floridum Roem. & Schult.	5%	47	
			Sonneratia alba Sm.	9%	85	
West Donan	0.02	6.60	*Ceriops decandra* (Griff.) Ding Hou	5%	43	857
			Xylocarpus granatum J.Koenig	1%	9	
			Bruguiera gymnorhiza (L.) Lam.	10%	86	
			Sonneratia caseolaris (L.) Engl.	10%	86	
			Rhizophora mucronata Lam.	10%	86	
			Rhizophora stylosa Griffith	19%	163	
			Avicennia marina (Forssk.) Vierh.	21%	180	
			Heritiera littoralis Dryand. ex Aiton	1%	9	
			Rhizophora apiculata Blume	23%	197	
West Pertamina	0.03	6.57	*Avicennia marina* (Forssk.) Vierh.	22%	285	1295
			Excoecaria agallocha L.	1%	13	
			Bruguiera sexangula (Lour.) Poir.	3%	39	
			Ceriops tagal (Perr.) C.B.Rob.	5%	65	
			Xylocarpus granatum J.Koenig	5%	65	
			Rhizophora stylosa Griffith	25%	324	
			Nypa fruticans Wurmb	10%	130	
			Rhizophora apiculata Blume	23%	298	
			Heritiera littoralis Dryand. ex Aiton	6%	78	
Kalipanas River	0.04	7.59	*Rhizophora mucronata* Lam.	9%	55	607
			Avicennia marina (Forssk.) Vierh.	12%	73	
			Rhizophora stylosa Griffith	12%	73	
			Xylocarpus granatum J.Koenig	10%	61	
			Sonneratia caseolaris (L.) Engl.	8%	49	
			Bruguiera gymnorhiza (L.) Lam.	8%	49	
			Thespesia populnea (L.) Sol. ex Corrêa	3%	18	
			Melaleuca leucadendra (L.) L.	7%	42	
			Rhizophora apiculata Blume	15%	91	
			Xylocarpus moluccensis (Lam.) M.Roem.	5%	30	
			Heritiera littoralis Dryand. ex Aiton	3%	18	
			Hibiscus tiliaceus L.	8%	49	

Table 5. The correlation between TPHs and mangrove density

Correlation	Water	Sediment	Mangrove density
Water TPHs	1		
Substrate TPHs	0.83	1	
Mangrove density	-0.083	-0.248	1

Table 6. The correlation among variables in mangrove ecosystem in East Segara Anakan Lagoon, Cilacap, Central Java, Indonesia

Correlation matrix (Pearson (n-1)):								
Variables	**TPHs Water**	**TPHs Sediment**	**Temperature**	**Water salinity**	**pH**	**TDS (mg/L)**	**Number of species**	**Density**
TPHs in water	1	0.831	0.818	-0.447	0.457	0.447	0.844	-0.083
TPHs in sediment	0.831	1	0.710	-0.560	-0.072	0.773	0.852	-0.247
Temperature	0.818	0.710	1	-0.146	0.158	0.326	0.714	-0.557
Water salinity	-0.447	-0.560	-0.146	1	0.048	-0.735	-0.505	0.051
pH	0.457	-0.072	0.158	0.048	1	-0.446	0.120	0.553
TDS (mg/L)	0.447	0.773	0.326	-0.735	-0.446	1	0.680	-0.354
Number of species	0.844	0.852	0.714	-0.505	0.120	0.680	1	-0.161
Density	-0.083	-0.247	-0.557	0.051	0.553	-0.354	-0.161	1

Table 7. Correlation matrix (Pearson n) among variables in East Segara Anakan Lagoon, Cilacap, Central Java, Indonesia, analysed using Principal Component Analysis

Variables	**Soil TPH**	**Water TPH**	**TPH of stem**	**TPH of leaves**	**TPH of roots**	**Mangrove density**
Soil TPH	1	0.874	-0.441	0.017	-0.358	-0.197
Water TPH	0.874	1	-0.267	0.022	-0.126	-0.395
TPH of stem	-0.441	-0.267	1	0.379	0.428	-0.185
TPH of leaves	0.017	0.022	0.379	1	0.327	0.052
TPH of roots	-0.358	-0.126	0.428	0.327	1	0.071
Mangrove density	-0.197	-0.395	-0.185	0.052	0.071	1

Note: Values in bold are different from 0 with a significance level alpha at 0.95

Table 8. The eigenvalue of research stations in East Segara Anakan Lagoon, Cilacap, Central Java, Indonesia, analysed using principal component analysis

	F1	**F2**
Eigenvalue	4.295	1.849
Variability (%)	53.693	23.110
Cumulative %	53.693	76.803
Sapuregel	**-3.651**	1.309
East Pelawangan	**-1.034**	-0.671
West Sleko	-0.263	**-2.027**
West Prenca	**0.790**	-0.084
West Donan	0.372	**-1.115**
West Pertamina	0.595	**1.628**
Kalipanas	**3.191**	0.960
TPHs water	**0.761**	0.218
TPHs sediment	**0.901**	0.000
Temperature	**0.622**	0.022
Water salinity	**0.407**	0.013
pH	0.000	**0.941**
TDS (mg/L)	**0.626**	0.201
Number of species	**0.844**	0.029
Density	0.135	**0.426**

The cluster of mangrove species density

Principal component analysis was used to cluster the density of mangrove species using Pearson correlation, Kaiser-Meyer-Olkin correlation, and Bartlett's sphericity test at 95% level of significance. The result shows that the correlation between soil and water TPHs was TPHs stem > TPHs roots > TPHs leaves (Table 7). Water TPHs and sediment TPHs negatively affected mangrove density although the correlation was weak. TPHs in water showed a strong correlation with TPHs in sediment, while there was a weak negative correlation with TPHs in stems and roots. TPHs in sediment resemble those in water, and TPHs in sediment exhibited a weak negative correlation with TPHs in stems and roots.

Table 9 shows the eigenvalue of the mangrove species cluster. Essentially, PCA indicated that the variability of F1 reached 40.142%, while F2 was 25.511%. The eigenvalue analysis indicated that soil TPHs, water TPHs, and stem TPHs had eigenvalue F1 greater than the eigenvalues for F2, F3, F4, F5, and F6. TPHs of leaves (F2 highest value), TPHs of roots (F4 highest value), and mangrove density (F3 highest value). Species distribution indicated that the species with the highest F1 were *Aegiceras corniculatum* (L.) Blanco, *Bruguiera gymnorhiza* (L.) Lam., *E. agallocha, Melaleuca leucadendra* (L.) L., *N. fruticans, R. mucronata, R. stylosa, S. caseolaris, T. populnea, Xylocarpus granatum* J.Koenig and *Xylocarpus molucensis* (Lam.) M.Roem.. The mangrove species with the highest F2 were *A. marina*, *Heritiera litoralis* Dryand. ex Aiton and *R. apiculata* while other species had highest of F3-F5.

The combined analysis of clustering TPHs in the research stations and the distribution of mangrove species showed that *M. leucadendra*, *T. populnea, Hibiscus tiliaceus* L., *X. moluccensis* are able to live in Kalipanas Station; *B. sexangula, E. agallocha* and *N. fruticans* in West Pertamina; *Acrostichum aureum* L., *A. corniculatum, Aegiceras floridum* Roem. & Schult., and *Sonneratia alba* Sm. in West Prenca and *Avicennia alba* Blume in West Sleko. However, *S. caseolaris* could be found in East Pelawangan, West Prenca, West Donan, and Kalipanas, *C. tagal* in Sapuregel and West Pertamina, *R. apiculata* in Sapuregel, West Prenca, West Donan and Kalipanas, *B. gymnorhiza* in West Donan, Kalipanas and West Prenca, *X. granatum* in West Donan, Kalipanas and West Pertamina, *A. Marina* in West Prenca, West Donan, Kalipanas and West Pertamina, *R. stylosa* in West Prenca and Kalipanas and *R. mucronata* in West Prenca, West Sleko, West Donan and Kalipanas (Table 10 and Figure 4).

Table 9. The eigenvalue of mangrove species in East Segara Anakan Lagoon, Cilacap, Central Java, Indonesia, analysed using principal component analysis

Item	F1	F2	F3	F4	F5	F6
Eigenvalue	2.409	1.531	1.003	0.643	0.348	0.067
Variability (%)	40.142	25.511	16.709	10.715	5.798	1.124
Cumulative %	40.142	65.653	82.362	93.077	98.876	100
Soil TPH	**0.802**	0.075	0.069	0.000	0.021	0.033
Water TPH	**0.661**	0.245	0.009	0.037	0.018	0.030
TPH of stem	**0.423**	0.293	0.075	0.033	0.175	0.000
TPH of leaves	0.089	**0.419**	0.273	0.165	0.053	0.000
TPH of roots	0.339	0.212	0.034	**0.406**	0.007	0.002
Mangrove density	0.095	0.285	**0.543**	0.002	0.074	0.001
Aal	0.006	0.356	0.002	**0.623**	0.011	0.003
Aau	0.1	0.031	**0.505**	0.282	0.082	0
AC	**0.748**	0.029	0.008	0.166	0.048	0
AF	0.015	0.128	**0.565**	0.274	0.019	0
AM	0.265	**0.632**	0.039	0.033	0.029	0.001
AM	0.265	**0.632**	0.039	0.033	0.029	0.001
AM	0.265	**0.632**	0.039	0.033	0.029	0.001
AM	0.265	**0.632**	0.039	0.033	0.029	0.001
BG	**0.818**	0.019	0.127	0.004	0	0.032
BG	**0.818**	0.019	0.127	0.004	0	0.032
BG	**0.818**	0.019	0.127	0.004	0	0.032
BS	0.435	0.006	**0.534**	0.009	0.001	0.016
CD	0.231	0.083	**0.286**	0.017	0.214	0.168
CT	0.145	0.255	0.003	**0.492**	0.103	0.002
CT	0.145	0.255	0.003	**0.492**	0.103	0.002
EA	**0.346**	0.07	0.324	0.002	0.249	0.008
HL	0.192	0.341	0.015	**0.414**	0.021	0.017
HL	0.192	0.341	0.015	**0.414**	0.021	0.017
HT	0.037	**0.608**	0.239	0.093	0.021	0.003
ML	**0.685**	0.075	0.093	0.022	0.123	0.001
NF	**0.431**	0.28	0.01	0.102	0.037	0.14
RA	0.088	**0.539**	0.357	0.007	0.009	0.001
RA	0.088	**0.539**	0.357	0.007	0.009	0.001
RA	0.088	**0.539**	0.357	0.007	0.009	0.001
RA	0.088	**0.539**	0.357	0.007	0.009	0.001
RM	**0.758**	0.184	0	0.012	0.041	0.005
RM	**0.758**	0.184	0	0.012	0.041	0.005
RM	**0.758**	0.184	0	0.012	0.041	0.005
RM	**0.758**	0.184	0	0.012	0.041	0.005
RS	**0.387**	0.036	0.349	0.002	0.222	0.003
RS	**0.387**	0.036	0.349	0.002	0.222	0.003
SA	0.252	0.001	0.071	0.111	**0.563**	0.002
SC	**0.53**	0.003	0.415	0.02	0.027	0.005
SC	**0.53**	0.003	0.415	0.02	0.027	0.005
SC	**0.53**	0.003	0.415	0.02	0.027	0.005
SC	**0.53**	0.003	0.415	0.02	0.027	0.005
TP	**0.811**	0.028	0.145	0.002	0.014	0
XG	**0.761**	0	0.02	0.04	0.119	0.059
XG	**0.761**	0	0.02	0.04	0.119	0.059
XG	**0.761**	0	0.02	0.04	0.119	0.059
XM	**0.391**	0.209	0.027	0.355	0.002	0.015

Figure 4 also explains that quadrant 1 was dominated by *R. mucronata*, *A. alba*, *Heritiera littoralis* Dryand. ex Aiton, and *B. gymnorhiza*. The quadrant 2 was dominated by *H. tiliaceus*, *E. agallocha*. *X. molucensis*, *Melaleuca leucadendra* (L.) L., *T. populnea*. Quadrant 3 was dominated by *S. caseolaris*, *R. stylosa*, *R. apiculata*, *C. decandra*, *B. sexangula*, *X. granatum*, *N. fruticans* and quadrant 4 was dominated by *S. alba*, *A. corniculatum*, *A. aureum*, *C. tagal*, *A. marina* and *A. floridum*.

The combined analysis of research stations (representing varying TPHs contamination level) and mangrove species density in Figure 5 explains that the clustering of *M. leucadendra, T. populnea, H. tiliaceus* and *X. moluccensis* in one station showed the similar adaptation of mangrove species to reduce the impacts of TPHs. The similar condition also occurred for *B. gymnorhiza, E. agallocha* and *N. fruticans* (one cluster) and *A. aureum, A. corniculatum, A. floridum* and *S. alba* (one cluster). However, the clustering of Kalipanas Station had variation of mangrove species because of varying TPHs levels, i.e. near the TPHs contaminant source, near the oil refinery industry and specific environment condition. Kalipanas as the mangrove habitat near oil refinery industry required the variation adaptation of mangrove species to live and grow in this TPHs contaminant area.

Table 10. The distribution of mangrove species in research stations representing varying TPHs

Stations	Soil TPHs	Water TPHs	TPHs of stem	TPHs of leaves	TPHs of roots	Mangrove density (trees ha^{-1})
EP, WPr, WD, KP	7.049	0.024	0.21	0.17	0.34	352
KP	7.963	0.037	0.34	0.07	0.01	42
KP	7.963	0.037	0.24	0.04	0.01	18
KP	7.963	0.037	0.34	0.51	0.54	117
KP	7.963	0.037	0.24	0.05	0.82	30
SP, WP	6.117	0.020	0.29	0.07	0.61	602
SP, WPr, WD, KP	6.744	0.020	0.18	0.12	0.26	1340
WD	6.833	0.017	0.19	0.09	0.25	43
WD, KP, WPr	5.556	0.018	0.37	0.14	0.57	181
WD, WP, KP	6.810	0.022	0.24	0.14	0.34	134
WP	6.567	0.027	0.25	0.04	0.23	39
WP	6.567	0.027	0.20	0.13	0.29	13
WP	6.567	0.027	0.21	0.10	0.01	500
WP, KP	5.932	0.024	0.34	0.15	0.92	104
WPr	5.667	0.013	0.47	0.08	0.01	75
WPr	5.667	0.013	0.33	0.18	0.41	253
WPr	5.667	0.013	0.32	0.09	0.01	47
WPr	5.667	0.013	0.25	0.20	0.42	73
WPr, WD, WP, KP,	5.633	0.013	0.21	0.10	0.48	926
WS	6.440	0.028	0.30	0.13	0.92	105
WS, KP	7.398	0.027	0.25	0.12	0.32	1037
WS, WPr, WD, KP	5.689	0.014	0.52	0.23	0.74	291

Note: EP: East Pelawangan, WPr: West Prenca, WD: West Donan, KP: Kalipanas, WP: West Pertamina, WS: West Sleko, SP: Sapuregel

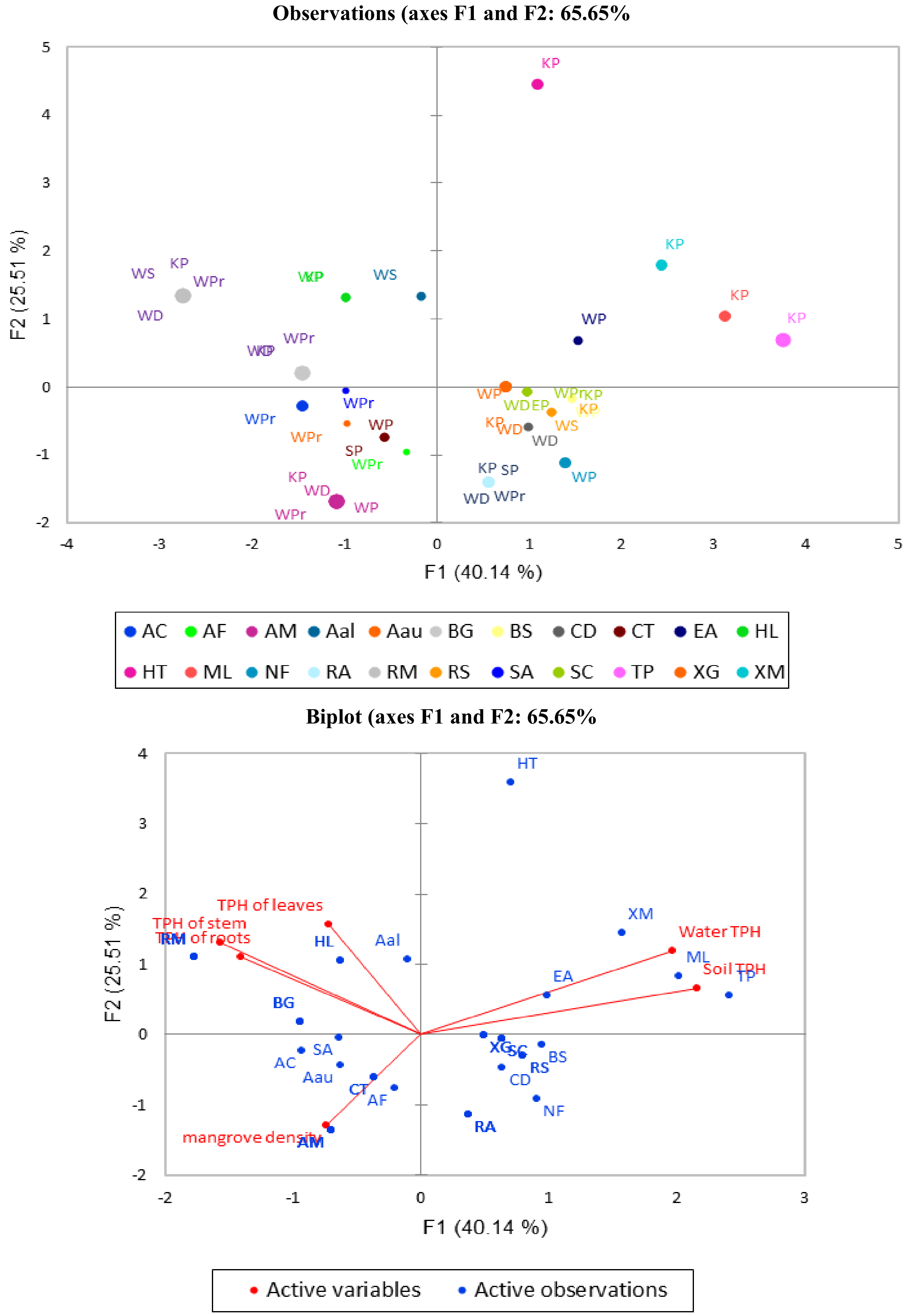

Figure 4. Distribution of mangrove species using PCA analysis

Note: AC: *Aegiceras corniculatum*, AF: *Aegiceras floridum*, AM: *Avicennia marina*, Aal: *Avicennia alba*, Aau: *Acrostichum aureum* L., BG: *Bruguiera gymnorhiza*, BS: *Bruguiera sexangula*, CD: *Ceriops decandra*, CT: *Ceriops tagal*, EA: *Excoecaria agallocha*, HL: *Heritiera litoralis*, ML: *Melaleuca leucadendra*, NF: *Nypa fruticans*, RA: *Rhizophora apiculata*, RM: *Rhizophora mucronata*, RS: *Rhizophora stylosa*, SA: *Sonneratia alba*, SC: *Sonneratia caseolaris*, TP: *Thespesia populnea*, XG: *Xylocarpus granatum*, XM: *Xylocarpus mucronata* (L.) R. Br.

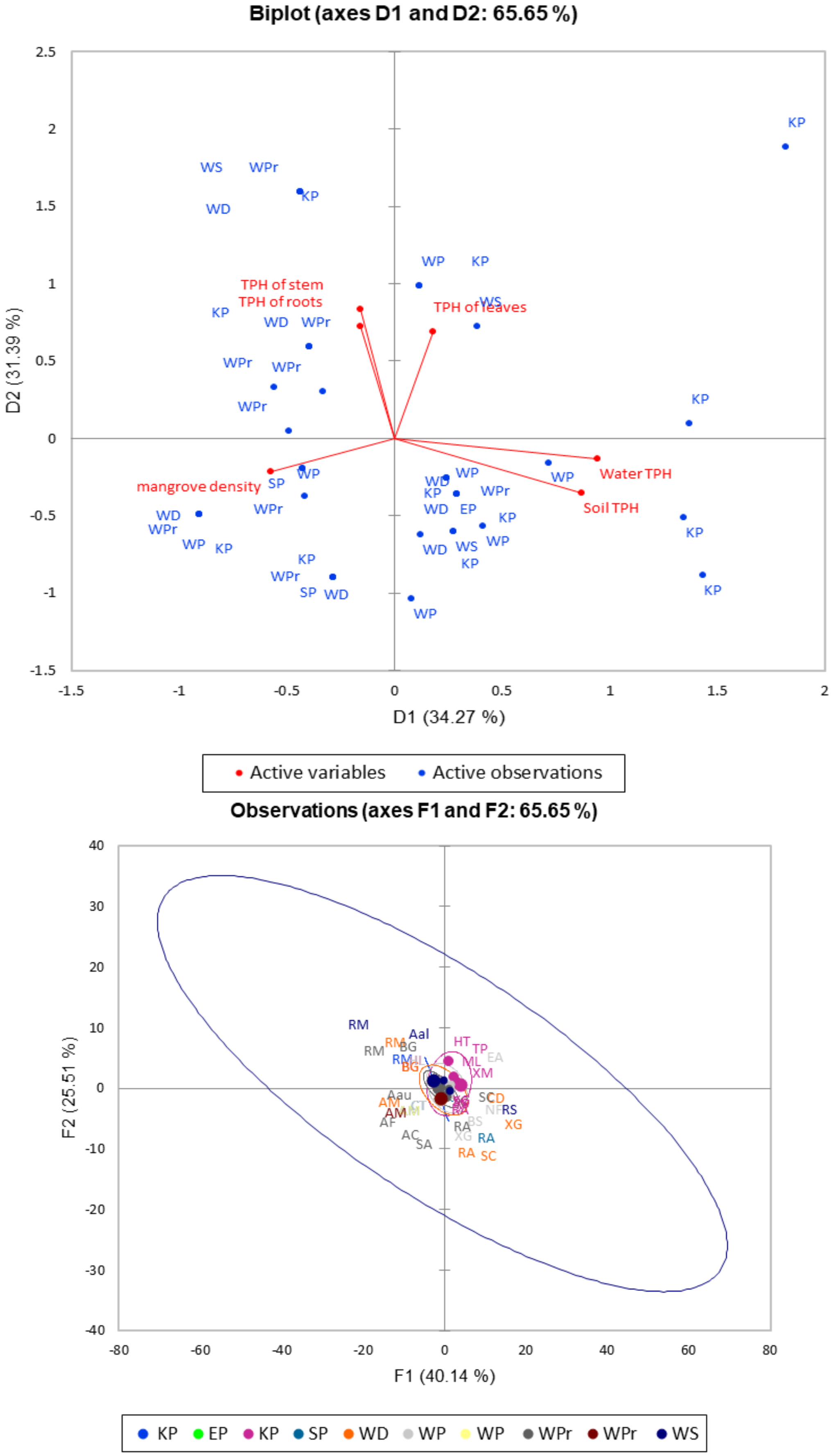

Figure 5. The combined analysis of mangrove species density and research stations representing varying TPHs contamination levels. Note: EP: East Pelawangan, WPr: West Prenca, WD: West Donan, KP: Kalipanas, WP: West Pertamina, WS: West Sleko, SP: Sapuregel

Discussion

Dominant mangrove species

East Segara Anakan Lagoon is dominated by *R. apiculata, R. stylosa,* and *A. marina,* suggesting that these species are highly adapted with petroleum hydrocarbons contaminant (Hilmi et al. 2021a, b, c, et al. 2022). The adaptation mechanism of mangrove species is developed through regeneration, physiological and morphological adaptation, and root metabolism (Ameen et al. 2016; Ballesteros et al. 2016; Abbasi and Keshavarzi 2019; Hilmi et al. 2023a, c). Hilmi et al. (2021a) found that the environmental factors influencing mangrove growth are water depth between 0.20-23.7 m and water inundation between 480cm; soil texture of clay and loam, soil nitrate of 1.5 mg 100 g^{-1}, soil phosphate of 1.5 mg 100 g^{-1}, C organic of 1.31%, soil pH of 6-7, debit between 0.360.73 m s^{-1}, single and semi double-type tides, and soil salinity of 6.5-10 ppt.

Species with the largest density included *R. apiculata* (1340 trees ha^{-1}), *R. stylosa* (1037 trees ha^{-1}), *A. marina* (976 trees ha^{-1}), *C. tagal* (602 trees ha^{-1}*)* and *N. fruticans* (500 trees ha^{-1}), indicating that these species had good adaptation to reduce impact of TPHS contaminants. To mitigate the effects of TPHs contamination, mangrove species need to exhibit robust growth and survival in contaminated zones through activities such as rapid growth, root adaptation, and metabolic processes like phytovolatization, phytodegradation (phytotransformation), phytostimulation, phytostabilization, and phytoextraction (Schwarzer et al. 2016; Analuddin et al. 2017; Win et al. 2019; Bomer et al. 2020; Hilmi et al. 2021a, et al. 2023a). Mangroves possess a unique metabolism that mitigates the effects of TPH contaminants via their specialized root structures, pneumatophore system, zoning system, affinity system, and landscape system (Hilmi et al. 2021b, c, et al. 2022). Mangrove also have the high bioactive compound to reduce the impacts of petroleum hydrocarbon for example phenolic, flavonoid, and tannin (Sharma 2019; Hilmi et al. 2021d). Bioactive compounds help mangroves perform internal detoxification and manage oxidative stress caused by TPHs contaminants.

Hilmi et al. (2021c) revealed that most area of Segara Anakan are dominated by *A. corniculatum, A. marina, R. apiculata, R. mucronata, R. stylosa, N. fruticans* and *S. alba.* Sreelekshmi et al. (2018) also found that the dominant species in a mangrove forest in Kerala, India, are *R. mucronata, R. apiculata, C. tagal, Kandelia candel* (L.) Druce*, S. alba,* and *S. caseolaris.* The dominant species in East Segara Anakan Lagoon was influenced by water and soil salinity, water and soil pH, water inundation, sea tide, soil texture, conversion and logging activities (Hilmi et al. 2021a, b, c, et al. 2022)

The correlation between mangrove density with TPHs contaminants

Total petroleum hydrocarbon contaminants have a significant effect on mangrove environments and ecosystems (Al Hoqani et al. 2025; Pidlisnyuk et al. 2025) including mangrove density. Overall, petroleum hydrocarbons in water and sediment present ongoing environmental issues (Grobelak et al. 2020; Júnior et al. 2020; Al Hoqani et al. 2025) and negatively impact environmental quality and pose a significant risk to the health of plants and animals (Pidlisnyuk et al. 2025). This requires understanding the potential for TPHs to build up in organisms and their harmful effects on species and ecosystems (Al Hoqani et al. 2025). Wei et al. (2022) also observed that total petroleum hydrocarbons found in coastal marine sediments can greatly threaten the aquatic environment and the health of ecosystems.

In East Segara Anakan Cilacap, the potential TPHs in water ranged from 0.01% to 0.06%, while in the sediment/substrate varied between 2.0% and 8.34%. Kalipanas River exhibited the highest TPH levels in both water and sediment due to its proximity to the petroleum waste disposal site. Wu et al. (2025) states that TPH contaminants enter the water environment, reaching concentrations of 0.06-35.33 mgL^{-1}, which negatively affect the growth and life of organisms. Taheri et al. (2022) states that the TPH concentration in the sediment sample was 6.35 ± 2.42, with values varying from 3.20 to 10.89 mg kg^{-1}. TPHs are harmful pollutants to the ecosystem and dangerous to human health and classified as organic pollutants, being endured in the environment and potentially harmful to various organisms and human health (Moreira et al. 2011). Ishola et al. (2025) found that in Orile-Igannu, the levels of TPHs contaminants varied from 1.2 to 3.75 mg kg^{-1}in contaminated regions, whereas in uncontaminated regions, they ranged from 0.14 to 0.79 mg kg^{-1}. This suggests that TPHs strongly correlate with high resistivity anomalies found in both contaminated and uncontaminated areas. Iheme et al. (2025) states that oil spills and petroleum hydrocarbons degrade very slowly through natural and biological processes, disperse, and are oxidized by sunlight. Soil contamination by petroleum hydrocarbons can change the physical and chemical properties of both surface and subsoil, and negatively impact plant growth, crop yields, and seed germination (Iheme et al. 2025).

Previous studies showed that TPHs contaminants adversely affect mangrove density and distribution, hastened mangrove deterioration, and root disruption (Cahyo et al. 2024; Hilmi et al. 2021c, et al. 2024). According to Table 3, Kalipanas exhibited the highest TPHs levels, with potential TPHs in soil ranging from 7.12 to 8.34% and in water from 0.1 to 0.06%. This suggests that TPHs lead to a reduced mangrove density, measured at just 607 trees per hectare. The existence of crude oil and its by products in the root zone and submerged mangroves has caused harmful effects on mangrove vitality and has markedly affected soil permeability, root coating, and direct adsorption (Siddique et al. 2024). Total petroleum hydrocarbons also affect the adaptation of mangrove species.

Based on correlation analysis, TPHs in both water and sediment had an insignificant effect on mangrove density, yet they still negatively affect it. This is indicated by the weak correlation between TPH contaminants and mangrove density. This finding suggests that the density of mangroves is not influenced exclusively by the presence of TPHs. Nonetheless, TPHs contaminants at high concentration might adversely affect mangrove ecosystems, as TPHs and other pollutants elevate mangrove death rates, obstruct growth, and lead to diminished reproduction rates (Moreira et al. 2011; Hilmi et al. 2021c, et al. 2023a)

TPHs contaminant can continue to harm mangrove ecosystems and microbial functions, as mangrove species are crucial for biodiversity, microbial productivity, nutrient cycles, and adaptation. Consequently, harm to mangroves will affect the stability of ecosystems, organisms, and their environments (Siddique et al. 2024). The m-ERM-Q from this study ranged from 0.002 to 0.018 (mean 0.007) and is ≤ 0. The presence of TPHs contaminants in sediments can result in a 9% toxicity probability (Yan et al. 2023), affecting mangrove and aquatic species such as swimming crabs, estuarine shrimp, tiger prawns, periwinkles, and tilapia (Saunders et al. 2022). Petroleum hydrocarbons significantly affect the leaf surfaces of living mangrove seedlings, resulting in slower growth (Sun et al. 2013; Saunders et al. 2022). The slower growth of mangrove seedlings can greatly affect mangrove density

Clustering of mangrove species based on the adaptation of mangrove species to TPHs contaminant

The cluster of research stations. The clustering of mangrove stations in TPHs contaminated areas revealed that Kalipanas River and West Pertamina share similar characteristics (first cluster), while West Prenca and West Donan form the second cluster, and West Sleko and East Pelawangan comprise the third cluster. Sapuregel, however, possesses distinct characteristics compared to other regions. The density of mangroves shows a strong negative correlation with water TPHs, a moderate negative correlation with temperature, a moderate positive correlation with pH, and weak correlations with other variables. Sediment TPHs shows a strong positive correlation with water TPHs, temperature, and TDS, while it has a negative correlation with water salinity, pH, and mangrove density. Water TPHs show a strong correlation with sediment TPHs, temperature, and species number, while displaying a weak correlation with pH, water salinity, and TDS, and a very weak correlation with mangrove density. The TPHs pollutant adversely affects the stability of coastal and mangrove ecosystems (Hilmi et al. 2015; Abbasi and Keshavarzi 2019; Al-Haddad et al. 2022; Al Hoqani et al. 2025; Ishola et al. 2025). Essentially, the ecological conditions as indicators of the clustering of mangrove stations indicated that sediment TPH affects > species number > water TPH > TDS > temperature > water salinity > mangrove density and pH. Ecological factors suggest that water TPH and sediment TPH significantly affect mangrove stability in the ecosystem.

Kalipanas River and West Pertamina are in the proximity to contamination sources (i.e. oil refinery area), making them directly exposed to petroleum hydrocarbons. Kalipanas Station, along with nearby TPHs sources, shows the greatest potential for water and sediment TPHs, impacting the potential density of mangroves (just 607 trees/ha). Typically, the existence of TPHs in water and sediments adversely affects environmental quality and presents considerable threats to trees, plants, and animals, including both aquatic and terrestrial species (Ballesteros et al. 2016; Al-Haddad et al. 2022; Al Hoqani et al. 2025; Pidlisnyuk et al. 2025) such as mangroves. Wei et al. (2022) also observe that total petroleum hydrocarbons (TPHs) in coastal ecosystems pose significant concern and severe threat to disrupt the aquatic environment and ecosystem health

Essentially, TPHs contamination affects the stability of mangrove, lagoon, and coastal ecosystems due to the biological and chemical processes that necessitate adaptation for survival and growth (Esmaeili and Saremnia 2018; Abbasi and Keshavarzi 2019; Wei et al. 2022). TPHs affect the habitats of organisms, ecosystem, human settlement, soil stability, productivity, and water quality (Grobelak et al. 2020; Raja et al. 2022; Moses et al. 2023; Wu et al. 2025; Zhang et al. 2023). The grouping of research stations revealed variations in potential TPHs, environmental characteristics, and effects on humans, as well as terrestrial and aquatic organisms, including mangrove species (Hilmi et al. 2015; Khudur and Ball 2018; Taheri et al. 2022; Moses et al. 2023). Stations in proximity to refineries are expected to exhibit elevated TPH contamination levels, which will greatly affect mangrove density. Consequently, the mangrove species need to be well adapted to thrive and develop in areas impacted by TPH contamination (Moreira et al. 2011; Hilmi et al. 2021c, et al. 2023a).

The cluster of mangrove species. There are four clusters of mangrove species which indicates adaptation in TPHs contaminant area in Segara Anakan Cilacap, i.e. first cluster consisted of *A. corniculatum*, *B. gymnorhiza*, *E. agallocha*, *M. leucadendra*, *N. fruticans*, *R. mucronata*, *R. stylosa*, *S. caseolaris*, *T. populnea*, *X. granatum* and *X. molucensis*, while the second cluster included *A. marina*, *H. litoralis* and *R. apiculata*. Third cluster consisted of *S. caseolaris*, *R. stylosa*, *R. apiculata*, *C. decandra*, *B. sexangula*, *X. granatum* and *N. fruticans*; while Fourth Cluster composed by *S. alba*, *A. corniculatum*, *A. aureum*, *C. tagal*, *A. marina* and *A. floridum*.

The cluster of mangrove species adaptation was constructed by first Principal Component (PC1) exhibited moderate variability at just 40.14%, while the second principal component showed low variability (merely 25.51%). The PC 1 was affected by soil TPHs (0.802), water TPHs (0.661), and stem TPHs (0.423). The second Principal Component (PC2) was affected by leaf TPHs (0.419), while root TPH (0.406) was noted in PC4, and mangrove density (0.543) was observed in PC3. Previous studies state that TPHs are a prevalent category of organic pollutants in natural water systems, resulting in diverse adaptations of organisms to survive and thrive in polluted regions (Ani and Ochin 2018; Iheme et al. 2025; Wu et al. 2025). Petroleum, which includes crude oil and its derivatives, contains intricate organic compounds such as aliphatic (alkanes and cycloalkanes) and aromatic hydrocarbons, significantly influencing the stability needed for organisms to live and grow (Ahmadkalaei et al. 2021; Mirjani et al. 2021)

Ecologically, the results of principal component analysis represents the functional gradient from exposure to TPHs contaminants to internal buildup. In this situation, the trunk and roots serve as the primary areas for hydrocarbon storage. The root structure, directly interacting with polluted sediments, probably serves as the primary location for absorption. The stem, being the largest component of the tree's biomass, serves to gather and transport TPHs to the leaves. The capacity of mangrove species to adjust to TPHs in water and sediment influences the possible density of mangrove species. PC1 illustrates the function of the storage and buffer compartment in relation to mangrove density and the potential for TPHs contamination. According to Figures 4 and 5, the PC1 structure accounts for the highest share of variance while also corresponding to ecological interpretations, indicating that the trunk and roots serve as protective barriers, lessening the effects on mangrove species density. The comparatively reduced TPHs load in leaf tissue in PC1 and elevated levels in PC2 further reinforce the idea that TPHs greatly affect mangrove species density.

The adaptation pattern of mangrove species in TPHs contaminant area give indication that this species can grow and live in this area. The adaptation mechanism can be used to support the activity of TPHs reduction with concept of fitoremediation, filtration model (Esmaeili and Saremnia 2018; Khudur and Ball 2018; Moses et al. 2023; Iheme et al. 2025), mangrove landscaping (Moreira et al. 2011; Hilmi et al. 2023c), and combination model between fitoremediation and polluted filtration (Moreira et al. 2011; Moses et al. 2023; Zhang et al. 2023). Bassically, Total Petroleum Hydrocarbons (TPHs), composed of carbon (C) and hydrogen (H), represent a measurable quantity of numerous hydrocarbon molecules derived from crude oil that pose significant risks to humans, animals, and plants. Mangroves, as a variety of trees, possess the capability to take in petroleum hydrocarbons (PHCs), which can accumulate in the soil and water. Mangroves have the capability to biologically accumulate substances to diminish the risk of petroleum (Moreira et al. 2011; Iheme et al. 2025).

The different species domination in TPHs contaminant area is influenced by the adaptation of mangrove species. The data showed that *M. leucadendra, T. populnea, H. tiliaceus* and *X. moluccensis* were only found in Kalipanas Station. The similar condition also showed that *B. sexangula, E. agallocha* and *N. fruticans* were only found in West Pertamina, *A. aureum, A. corniculatum, A. floridum* and *S. alba* only occurred in West Prenca and *A. alba* in West Sleko. This condition showed that these mangrove species have restricted and limitation of adaptation to reduce impact of fuel oil spill, potential of soil and water fertilization (Scarlett et al. 2024), the toxicity of oil spill contamination (Odisu et al. 2021), and supporting microorganisms to support mangrove life and growth. The TPHs contaminant can decrease the survival rate of mangrove species, increasing of mangrove mortality and decreasing ability of mangrove species distribution (Hilmi et al. 2023b, et al. 2024). However, *S. caseolaris* was found in East Pelawangan, West Prenca, West Donan, and Kalipanas, while *C. tagal* in Sapuregel, and West Pertamina, *R. apiculata* in Sapuregel, West Prenca, West Donan and Kalipanas, *B. gymnorhiza* in West Donan, Kalipanas and West Prenca, *X. granatum* in West Donan, Kalipanas and West Pertamina, *A. marina* in West Prenca, West Donan and Kalipanas and West Pertamina, *R. stylosa* in West Prenca and Kalipanas and *R. mucronata* in West Prenca, West Sleko, West Donan and Kalipanas.

Sonneratia caseolaris, *C. tagal*, *R. apiculata*, *B. gymnorhiza*, *X. granatum*, *A. marina*, *R. stylosa* and *R. mucronata* as the dominant species have the ability to live and grow in TPHs contaminant area with bioaugmentation, bioaccumulation, biodegradation, bioextraction, biotransformation and biostabilization activities. To reduce the impacts of TPHs contaminant can be done by the phytoremediation activity of petroleum hydrocarbon using three mangrove species applied through tidal bioreactor (Hidayati et al. 2018). This activity needs to be done to reduce petroleum hydrocarbon as most common organic pollutant groups with derivatives such as gasoline, kerosene, paraffin, asphalt, which might have risks to spill to the environment.

In conclussion, TPHs contaminant had a significant impact on mangrove density, resulting in a reduction of mangrove density. Kalipanas Station showed the highest TPHs contaminant with a density of only 607 trees ha^{-1} (low density), unlike other stations that had a mangrove density ranging from 1092 trees ha^{-1} to 1295 trees ha^{-1}. Mangrove density had a negative correlation with TPHs in water with -0.083 (weak correlation), TPHs in sediment with -0.247 (weak correlation), temperature with -0.557 (moderate correlation), TDS with -0.354 (weak correlation), and have positive correlation with water salinity with 0.051 (weak correlation), pH with 0.553 (moderate correlation). There were four clusters of mangrove species in response to TPHs contaminant, namely first cluster (*R. mucronata, A. alba, H. littoralis,* and *B. gymnorhiza*); Second cluster (*H. tiliaceus, E. agallocha, X. molucensis, M. leucadendra* and *T. populnea*); Third cluster (*S. caseolaris, R. stylosa, R. apiculata, C. decandra, B. sexangula, X. granatum* and *N. fruticans*); Fourth cluster (*S. alba, A. corniculatum, A. aureum, C. tagal, A. marina* and *A. floridum*).

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