Effects of dieback on the vegetative, chemical, and physiological status of mangrove forests, Iran: Postprint

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Abstract

Mangrove forests are valuable resources in tropical and subtropical regions, which have been faced dieback due to various human activities including rapid expansion of shrimp farming, urban development, and pollution, as well as natural factors such as rising sea level, increasing air temperature, drought, and sharp decrease in rainfall. However, the mechanisms of dieback of mangrove forests are not well understood. Therefore, this research aimed to assess the vegetative, chemical, and physiological status of grey mangrove (Avicennia marina (Forsk.) Vierh.) forests at different intensities of dieback in the Hormozgan Province, Iran. A total of 40 plots categorized into four dieback intensities (severe, medium, low, and control) were randomly selected for monitoring, and various parameters related to vegetative, chemical, and physiological status of grey mangrove forests were examined. The results revealed that the control group had the highest tree density, seedling density, vitality levels, aerial root density, and aerial root height. Generally, as dieback severity increased, a decrease in demographic and vegetative parameters of trees and seedlings was observed in the dieback treatments. The amounts of heavy metals (lead, cadmium, and nickel) in the sediment, roots, and leaves of grey mangrove trees at different dieback levels indicated that lead levels were the highest in the sediment, roots, and leaves in the severe dieback treatment. At the same time, the control had the lowest values. Cadmium concentrations in the sediment followed the pattern of severe dieback>moderate dieback>low dieback>control with no significant differences in the roots and leaves. Nickel amounts in all three parts, i.e., sediment, roots, and leaves showed the highest levels in the severe dieback treatment. Furthermore, metal level analysis in the organs of grey mangrove trees at different dieback levels revealed that lead and nickel were more abundant in the root organ compared with the leaves. In contrast, the leaf organ exhibited the highest cadmium levels. Dieback significantly impacted water electrical conductivity (EC), soil organic carbon (SOC), and chlorophyll a, b, and total chlorophyll contents, with the highest values observed in the severe dieback treatment. However, no significant differences were observed in acidity and carotenoid levels. In conclusion, sediment erosion and heavy metal accumulation were critical contributors to dieback of grey mangrove trees, affecting their physiological, vegetative, and plant production characteristics. As the ability of these plants to rehabilitate has diminished, effective management planning is imperative in dieback-affected areas.

Full Text

Preamble

Effects of dieback on the vegetative, chemical, and physiological status of mangrove forests, Iran

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Abstract: Mangrove forests are valuable resources in tropical and subtropical regions that have experienced dieback due to various human activities including rapid expansion of shrimp farming, urban development, and pollution, as well as natural factors such as rising sea level, increasing air temperature, drought, and sharp decreases in rainfall. However, the mechanisms of mangrove forest dieback are not well understood. Therefore, this research aimed to assess the vegetative, chemical, and physiological status of grey mangrove (*Avicennia marina* (Forsk.) Vierh.) forests at different intensities of dieback in Hormozgan Province, Iran. A total of 40 plots categorized into four dieback intensities (severe, medium, low, and control) were randomly selected for monitoring, and various parameters related to vegetative, chemical, and physiological status of grey mangrove forests were examined. The results revealed that the control group had the highest tree density, seedling density, vitality levels, aerial root density, and aerial root height. Generally, as dieback severity increased, a decrease in demographic and vegetative parameters of trees and seedlings was observed in the dieback treatments. The amounts of heavy metals (lead, cadmium, and nickel) in the sediment, roots, and leaves of grey mangrove trees at different dieback levels indicated that lead levels were highest in the sediment, roots, and leaves in the severe dieback treatment, while the control had the lowest values. Cadmium concentrations in the sediment followed the pattern of severe dieback > moderate dieback > low dieback > control with no significant differences in the roots and leaves. Nickel amounts in all three parts—sediment, roots, and leaves—showed the highest levels in the severe dieback treatment. Furthermore, metal level analysis in the organs of grey mangrove trees at different dieback levels revealed that lead and nickel were more abundant in the root organ compared with the leaves. In contrast, the leaf organ exhibited the highest cadmium levels.

Dieback significantly impacted water electrical conductivity (EC), soil organic carbon (SOC), and chlorophyll a, b, and total chlorophyll contents, with the highest values observed in the severe dieback treatment. However, no significant differences were observed in acidity and carotenoid levels. In conclusion, sediment erosion and heavy metal accumulation were critical contributors to dieback of grey mangrove trees, affecting their physiological, vegetative, and plant production characteristics. As the ability of these plants to rehabilitate has diminished, effective management planning is imperative in dieback-affected areas.

Keywords: *Avicennia marina*; heavy metal; demographic characteristic; pneumatophores; mangrove forests

1 Introduction

From an ecological perspective, coastal habitats are among the most critical ecosystems on Earth. Among these habitats, mangrove forests stand out as one of the world' s most vital coastal systems due to their unique value. Mangrove forests are of significance to coastal governments because of the comprehensive ecosystem services they provide (Moslehi, 2018). Over the past decades, these ecosystems have undergone various changes due to human activities (Wang et al., 2021). Climate change, with its various components including sea level rise, temperature fluctuations, changes in atmospheric carbon dioxide concentration, oceanic cycle patterns, shifts in rainfall patterns, and the increased occurrence of storms, profoundly affects the health of mangrove forests. It is worth noting that these coastal areas face threats such as erosion, flooding, strong waves, and tsunamis. However, among all these factors, the most significant threat to mangrove forests is posed by human intervention, specifically pollution and deforestation (Delfan and Ghodrati-Shojaii, 2021).

Mangrove forest dieback represents one of the most pressing global threats to these ecosystems, yet limited information exists regarding its underlying mechanisms and influencing factors. Recent studies have begun to illuminate this issue. Ghosh et al. (2021), analyzing dynamic changes in mangrove forests using hyperspectral data from 2011 to 2014, found that increased salinity reduced mangrove proportions in some areas, though salt-tolerant species like *A. marina* and *Avicennia officinalis* Linn showed increased presence. Similarly, Duke et al. (2017) investigated large-scale mangrove loss in Australia’ s Gulf of Carpentaria during 2015-2016, attributing it to an extreme weather event characterized by high temperatures and low precipitation without hurricane-force winds. Nguyen et al. (2021) researched mangrove health in Thanh Hoa Province, Vietnam, focusing on fungal pathogens related to plant deterioration and identified four main fungal genera responsible for leaf spots and stem dieback. Mafi Gholami et al. (2017) investigated changes in Hormozgan Province mangrove forests from 1986 to 2016, finding that environmental factors like climate changes, local geomorphology, hydrology, and human activities limited forest development. Yaqoubzadeh et al. (2020) explored the impact of docks on vegetative and reproductive characteristics of mangrove trees in Khor-e-Azini Wetland and Khamir Port, Iran, revealing critically high nickel levels in sediments of *A. marina* and *Rhizophora mucronata* Poir. Other Persian Gulf region studies by AboHassan (2013), Al Hagibi et al. (2018), Saleh et al. (2018), and Aljahdali and Alhassan (2020) have reported heavy metal concentrations in sediments ranging from 14 to 98 µg/g for copper, 44 to 306 µg/g for zinc, and 8 to 99 µg/g for nickel. These results underscore the need to thoroughly investigate and control heavy metal pollution in Iranian mangrove forests. Additionally, sediment deposition is crucial in shaping vegetative and physical-chemical characteristics of mangrove trees. Nardin et al. (2021) researched the impact of sediment deposition on mangrove forests in the Mekong Delta, Vietnam, highlighting that significant deposition could bury mangrove roots and pneumatophores, leading to forest dieback.

Grey mangrove forests near ports, primarily used for refueling barges, are highly susceptible to fuel spills during refueling operations (Dittman et al., 2022). Unfortunately, grey mangrove forests face these pollution problems due to their proximity to pollution sources in Hormozgan Province, Iran. Consequently, these forests have undergone significant changes in recent years and are experiencing dieback. Given the multiple factors contributing to dieback, especially their proximity to pollution sources, this study aims to assess the vegetative, chemical, and physiological status of grey mangrove trees at different intensities of dieback.

2.1 Study area

Sirik Port, covering an area of 3500 km^2, is situated 75 km southeast of Minab on the coast of the Oman Sea (Bijani, 2019). The study area is within the Khor-e-Azini Wetland (26°18 02 -26°26 26 N, 57°03 26 -57°06 31 E), approximately 35 km from Sirik Port. The region experiences an average annual rainfall of 204.4 mm, ranging from 30.3 to 399.6 mm (Bijani, 2019; Moslehi et al., 2021), and exhibits a dry desert climate with pronounced water scarcity during the first nine months of the year (Kheirandish et al., 2015; Bijani, 2019).

Soil texture predominantly consists of silty loam in the surface soil (Moslehi et al., 2021), while the bottom soil is characterized by loam-clay-sand. Additionally, soil acidity (pH) ranges from 7.77 to 7.96, EC ranges from 27.29 to 46.90 dS/m, and SOC content varies from 0.34% to 1.33% (Sadeghi, 2005; Moslehi et al., 2021). Figure 1 [Figure 1: see original paper] shows the different intensities of dieback of grey mangrove trees in the Khor-e-Azini Wetland (Safyari, 2017).

2.2.1 Classification of dieback

In the study area, we assessed the severity of grey mangrove dieback based on multiple factors, including the number of dried trees, the proportion of trees exhibiting dieback symptoms, and the count of contaminated, dead, and healthy trees. Areas with over 50% of trees displaying signs of illness and dryness were classified as severe dieback, those with fewer than 50% dry and ailing trees as moderate dieback, and those with up to 15% showing sickness and dryness as low dieback (Fig. 1). Areas devoid of dieback served as control groups (Duke et al., 2003). The research employed a completely randomized design. After selecting both dried and control groups for each treatment, we randomly established 10 m × 10 m plots. Each treatment comprised 10 plots, with four distinct treatments, resulting in 40 total plots (Mafi Gholami and Jafari, 2020).

Fig. 1 Different intensities of dieback of grey mangrove trees in the Khor-e-Azini Wetland, Iran. (a) low dieback; (b) medium dieback; (c) severe dieback; (d) control.

2.2.2 Demography of grey mangrove trees

The vegetative characteristics and vitality level of all trees within each plot were measured and documented using the Swiss statistical method (Zubeiri, 2004). Tree vitality was assessed using qualitative characteristics including canopy shape, leaf color, and dry micro-branches, which were evaluated observationally and graded as good, medium, or poor (Kenshlo, 2004). Other variables under scrutiny included the height of sample trees, determined using a precision measuring tape (Komiyama et al., 2008), and the collar diameter (cm) assessed with a measuring tape (Komiyama et al., 2008). The canopy area was calculated by measuring the two perpendicular diameters of the canopy and employing Equation 1 (van Laar and Akca, 2007).

$$CC = \pi \times \left(\frac{CD}{2}\right)^2$$

where CC is the canopy area (m^2) and CD is the mean of the two perpendicular diameters of the canopy (m). The health status of both trees and investigated seedlings within each plot was categorized into three groups: healthy, sick, and dead (Duke et al., 2003). These categories were documented after observational evaluation (Table 1).

Table 1 Classification and characteristics of grey mangrove trees

Classification	Description
Healthy	Healthy leaves without any symptoms of disease
Wilted	Disease, yellow leaves (chlorosis), necrotic spots, leaf burn, canopy cover, and low foliage
Dead	Wholly dried up and dead

2.2.3 Demography of grey mangrove seedlings

Through examining the trees across different plots, we investigated the demography of grey mangrove seedlings in 5 × 5 quadrats of each plot. Tree density per square meter was recorded (Duke et al., 2003; Yaqubzadeh et al., 2020).

2.2.4 Height, status, and density of pneumatophores

To assess the condition of pneumatophores in each plot, we randomly selected ten aerial roots of grey mangrove trees and measured the distance from the tip of each aerial root to the sediment surface. To gauge the impact of sediment on dieback, we also measured and recorded the distance between the sediment surface and the cable roots. We identified five trees at the plot' s center and four corners to determine pneumatophore density. Micro-plots measuring 1 m × 1 m were established at 1-m intervals from the tree trunk, and the number of aerial roots within these micro-plots was tallied (Cue and Ninomiya, 2007). The count of aerial roots, serving as a valuable indicator to ascertain the number of pneumatophores buried by sediment in each plot, was averaged (n=5). This average was used to determine the density of aerial roots at each distance from the tree within a single plot (Duke et al., 2001; Duke et al., 2003).

2.2.5 Physiological properties

A systematic approach was employed to assess the physiological characteristics of grey mangrove trees within various treatments. Ten trees were selected randomly from each plot, and four leaves were collected, one from each cardinal direction. These four leaves were subsequently combined to create a composite sample. Ten such composite leaf samples were assembled for physiological analysis for every plot, yielding 40 leaf samples divided equally between control and dieback treatments. All collected samples were transported to the laboratory and promptly frozen using liquid nitrogen, then stored in a freezer at -80°C to maintain integrity. The Arnon method (1967) was employed to determine chlorophyll and carotenoid levels.

To initiate analysis, we placed 0.2 g of frozen leaves into a mortar and ground them thoroughly using liquid nitrogen. Then, 20 mL of 80% acetone was added to the sample and the mixture was filtered using a vacuum pump. We separated the plant residue from the liquid by centrifuging the solution at 2700 r/min for 10 min at 25°C. The upper extract was carefully transferred to a glass flask, and its volume was measured. A portion of this extract was subsequently poured into a spectrophotometer cuvette, and absorbance was read at wavelengths of 645, 663, and 470 nm. Pigment content (mg/g fresh weight) was calculated using the following equations (Khlifi et al., 2013).

$$\text{Chlorophyll a} = [12.7(A_{663}) - 2.69(A_{645})] \times \frac{V}{W}$$

$$\text{Chlorophyll b} = [22.9(A_{645}) - 4.68(A_{663})] \times \frac{V}{W}$$

$$\text{Total chlorophyll} = [20.2(A_{645}) + 8.02(A_{663})] \times \frac{V}{W}$$

$$\text{Carotenoid} = \frac{1000A_{470} - 1.8\text{Chl a} - 85.02\text{Chl b}}{198}$$

where A_{645}, A_{663}, and A_{470} are the optical absorption at wavelengths of 645, 663, and 470 nm of the samples, respectively; V is the final volume of ethanol consumed (mL); and W is the tissue weight (g).

2.2.6 Water properties

To ascertain the acidity and EC of water in each treatment, we randomly excavated three soil cores measuring 30 cm × 30 cm × 30 cm within each plot. After filling the pits with water, we transported water samples to the laboratory to determine acidity and EC (Duke et al., 2003). Measurements were conducted using pH and EC meters (Richard, 1954).

2.2.7 Chemical properties of sediment, roots, and leaves of grey mangrove trees

Five trees were randomly selected within each plot for sediment sampling in each dieback treatment. Soil samples were collected beneath the canopy in the rhizosphere area at a depth of 10 cm. Five sediment samples gathered in each plot were amalgamated, resulting in a composite sediment sample (10 sediment samples for each treatment, totaling 40 sediment samples) (Moslehi et al., 2021). Samples were combined to create composite samples for each organ, consisting of 10 leaf samples and 10 root samples for each dieback treatment (Machado et al., 2002). The combined root and leaf samples were first air-dried and subsequently subjected to complete drying at 75°C for 24 h (Einollahipeer et al., 2013). The collected sediment was also entirely air-dried in the shade. Dried sediment, leaf, and root samples were pulverized using a porcelain mortar and passed through a 63- m sieve to eliminate impurities and coarser particles. Subsequently, we added 5 mL of concentrated nitric acid (65%) to 0.5 g of dry matter. The prepared mixture was initially digested for 1 h at laboratory temperature and then for 3 h at 90°C on a hot plate. After cooling, the mixture was filtered using Whatman No. 42 filter paper, reaching a final volume of 50 mL with double-distilled water, thereby creating the desired extract for measuring metals. Samples were stored at 4°C. Heavy metals were measured using an atomic absorption device with a cathode lamp, expressed in mg/L (Dewis and Freitas, 1970). After sieving part of the sediment samples through a 2-mm mesh, 1 g of the resulting material was used to measure organic carbon through the Walky-Black oxidation method (Page et al., 1992). This study assessed three heavy metal elements: nickel, cadmium, and zinc.

2.3 Data analysis

Data analysis was conducted utilizing SPSS v.26.0. The normality of data distribution was assessed through the Kolmogorov-Smirnov test, while the homogeneity of variance was verified using the Levene test. All measured properties, chlorophyll, carotenoids, and leaf metals among different treatments, were analyzed using one-way analysis of variance (ANOVA). Mean comparisons were performed utilizing Duncan' s multiple-range test.

3.1 Demographic and vegetative characteristics of trees and seedlings

As shown in Table 2 , control trees exhibited the highest percentage of tree density, while density significantly decreased with increasing dieback severity. The number of ailing trees was notably increased under dieback treatments, particularly in cases of severe dieback, suggesting unfavorable conditions. Furthermore, the density and health of seedlings within each treatment were assessed, revealing that the highest percentage of seedling density occurred under control treatment, with decreases under other treatments reaching a minimum under severe dieback. As dieback severity increased, the number of healthy seedlings decreased, and their mortality rate concurrently increased (Table 2).

Table 2 Density of grey mangrove trees and seedlings under different dieback treatments

Plant type	Type of dieback	Plant density (%)	Healthy (%)
Grey mangrove trees	Control		
	Low dieback		
	Moderate dieback		
	Severe dieback		
Grey mangrove seedlings	Control		
	Low dieback		
	Moderate dieback		

Plant type	Type of dieback	Plant density (%)	Healthy (%)
	Severe dieback		

Results indicated a significant divergence in the vitality of grey mangrove trees across various dieback treatments ($P<0.01$). The highest vitality was observed under control treatment (4.28), demonstrating a substantial disparity compared with severe and moderate dieback treatments, which recorded values of 2.83 and 3.84, respectively (Fig. 2a [Figure 2: see original paper]). ANOVA showed a significant difference in aerial root density among grey mangrove trees at various distances from the tree under different dieback intensities ($P<0.01$). On average, aerial root density under control treatment was highest (103.62 cm/m^2), significantly greater than that observed under other treatments (Fig. 2b). Following the control treatment, low dieback treatment exhibited the highest aerial root density (85.36 cm/m^2). Conversely, aerial root density in moderate and severe dieback treatments fell within the same range, displaying no significant difference (Fig. 2b).

Aerial root height under control treatment (10.84 cm) exceeded those of low, medium, and severe dieback treatments (7.87, 7.92, and 7.79 cm, respectively; $P<0.01$; Fig. 2c). Additionally, cable root height to the sediment surface was lowest under severe dieback treatment (7.31 cm) and exhibited a significant difference ($P<0.01$) compared with control (11.39 cm), low dieback (11.20 cm), and medium dieback (11.19 cm) treatments (Fig. 2c). Height of grey mangrove trees exhibited a significant difference among treatments ($P<0.05$), with trees under low dieback treatment being the shortest (Fig. 2d). In contrast, the other treatments, including control, showed no significant differences in height, collar diameter, and canopy area (Fig. 2e and f).

3.2 Lead, cadmium, and nickel contents in the sediment, roots, and leaves of grey mangrove trees

Results revealed that the highest lead concentration in sediment occurred under severe dieback treatment, whereas the lowest was found under control. Specifically, lead concentration in sediment was 27.78 mg/L under severe dieback treatment, significantly different from the other three treatments ($P<0.05$; Fig. 3a [Figure 3: see original paper]). Similarly, in roots and leaves, lead concentrations were highest at 9.62 and 8.10 mg/L, respectively (Fig. 3b and c). Conversely, control treatment had the lowest lead concentrations in both roots and leaves (7.22 and 5.29 mg/L, respectively).

ANOVA results showed a significant difference in cadmium concentration only in sediment ($P<0.01$), with no significant difference observed in roots and leaves. Severe dieback treatment had the highest cadmium concentration (0.82 mg/L), followed by moderate dieback (0.71 mg/L), low dieback (0.66 mg/L), and control (0.55 mg/L) treatments (Fig. 4a [Figure 4: see original paper]). In roots, the highest and lowest cadmium concentrations were observed under severe dieback and control treatments, respectively, though no significant differences were observed in leaves and roots across treatments (Fig. 4b and c).

Nickel concentrations in sediment, roots, and leaves of grey mangrove trees significantly varied under different dieback treatments. The highest nickel concentration occurred in sediment under severe dieback treatment (141.08 mg/L; $P<0.01$; Fig. 5a [Figure 5: see original paper]). In roots, severe and moderate dieback treatments exhibited similar nickel concentrations (39.27 and 37.91 mg/L), with a significant difference ($P<0.01$) from low dieback and control treatments (33.74 and 30.15 mg/L, respectively) (Fig. 5b). Similarly, severe dieback treatment in leaves had the highest nickel concentration (1.53 mg/L; $P<0.05$). Notably, low dieback and control treatments exhibited similar nickel concentrations in leaves that did not significantly differ from each other (Fig. 5c).

3.3 Metal distribution in the organs of grey mangrove trees

Significant differences in lead concentration were found between roots and leaves, except for low dieback treatment, with lead concentration higher in roots than in leaves (Fig. 6a [Figure 6: see original paper]). Significant differences in cadmium concentration were observed in both root and leaf organs, except for low dieback treatment, with cadmium concentration higher in leaves than in roots (Fig. 6b). Nickel concentration was greater in roots than in leaves, and was considerably higher than other metals (Fig. 6c).

3.4 Water property and soil organic carbon

Significant differences in water EC were found across various dieback treatments ($P<0.01$), though no significant differences were observed in acidity ($P>0.05$). The highest EC value was 22.06 dS/m under severe dieback treatment and the lowest under control (Fig. 7a [Figure 7: see original paper]). Acidity levels under dieback treatments were higher than under control, albeit without statistical significance (Fig. 7b). Results demonstrated a significant difference in SOC among treatments ($P<0.01$), following the pattern: severe dieback (0.92%) > medium dieback (0.84%) > low dieback (0.67%) > control (0.64%) with significant differences (Fig. 7c).

3.5 Chlorophyll a, b, total chlorophyll, and carotenoid contents in leaves

Results revealed significant differences in chlorophyll a, b, and total chlorophyll under different treatments ($P<0.01$), while no significant difference was observed in carotenoid content ($P>0.05$). Chlorophyll a, b, and total chlorophyll concentrations were highest under control treatment and lowest under severe dieback treatment (Fig. 8 [Figure 8: see original paper]). Specifically, chlorophyll a and b were 1.89 and 1.03 mg/g, compared with other treatments within the same group (Fig. 8a and b). Additionally, total chlorophyll contents in control and low dieback treatments, measuring 2.92 and 2.83 mg/g respectively, were in the same category while showing a significant difference from medium (2.24 mg/g) and severe (1.45 mg/g) dieback treatments (Fig. 8c).

4 Discussion

Mangrove dieback reduces ecosystem functions and services, significantly impacting coastal protection, nutrient cycling, carbon sequestration, and habitat for biodiversity (Lovelock et al., 2017; Sippo et al., 2020; Budiadi et al., 2023). This study examined the demography and vegetative characteristics of grey mangrove trees experiencing different dieback levels, revealing that control treatment had the highest tree density, vitality, aerial root density, and aerial root height, with these parameters decreasing as dieback intensity increased. Numerous studies have shown that dieback affects species composition, density, health, and demography (Duke et al., 2001; Ellison and Zouh, 2012). This phenomenon may be attributed to salinity, heavy metals, pests, diseases, and climate change (Osorio et al., 2017). Furthermore, severe dieback treatment had the lowest cable root height near the sediment surface, indicating sediment erosion in areas with severe dieback intensity. Cable roots consistently exposed to anaerobic conditions as sediment accumulates can lead to mangrove tree death (Adams and Human, 2016). Sediment deposition can bury pneumatophores, suffocating mangrove roots and reducing grey mangrove health (Nardin et al., 2021).

No significant differences were observed between dieback treatments regarding tree height, likely due to the relatively short investigation duration and the fact that these trees have reached maturity. Long-term monitoring is essential for more comprehensive understanding. The study of seedling demographic and vegetative characteristics revealed that all vegetative characteristics, including seedling density and height, were highest under control treatment but decreased under dieback treatments. Young individuals such as seedlings are highly susceptible to various factors contributing to mangrove dieback. Awal (2014) suggested that significant differences in mangrove regeneration can be observed, and the direct cause may not necessarily be dieback itself.

Regarding heavy metal impacts on mangrove forests, numerous studies including Hoq et al. (2002), Sarkar et al. (2003), Sarika and Chandramohanakumar (2008), Awal et al. (2009), and Awal (2014) have demonstrated their role in mangrove forest dieback. Heavy metals such as lead, cadmium, and nickel are potentially toxic to plants, microbes, aquatic animals, and humans (Dubinski et al., 1986). Our research found varying heavy metal levels in sediment, roots, and leaves across different dieback treatments. Lead concentrations were highest in sediment under severe dieback treatment and lowest under control. Roots and leaves contained the highest lead concentrations under severe dieback treatment, while control treatment had lower concentrations. High lead levels can cause symptoms of metal excess, potentially leading to vascular blockages in plants

(Yim and Tam, 1999) and ultimately reducing plant growth (MacFarlane and Burchett, 2002). Regarding cadmium, our results indicated a significant difference only in sediment across treatments, with no significant difference in roots and leaves. Due to higher cadmium concentrations under severe dieback compared with other treatments and control, it can be considered a factor contributing to grey mangrove dieback. Similarly, the highest nickel concentrations in sediment, roots, and leaves were found under severe dieback treatment. These findings imply that heavy metals play important roles in increasing dieback incidence in grey mangrove trees. Indeed, Awal (2014) reported that metal effects on dieback may be more related to amounts present in plant tissues rather than in sediment.

In this study, lead concentrations under different dieback treatments (except low dieback) were higher in roots than in leaves, while cadmium concentrations showed the opposite pattern. According to environmental quality standards, cadmium thresholds for biota and sediment were 0.001 and 0.700 mg/L, respectively (Dermawan et al., 2019). Our findings indicated high cadmium toxicity under severe dieback treatment for sediment, with no significant difference in roots and leaves (Dermawan et al., 2019). Nickel amounts in the two organs under different treatments showed that roots had higher levels than leaves. Internal physiological mechanisms enable mangroves to tolerate heavy metals (Awal, 2014). Our results indicated that the main metals in Iranian mangrove forests were cadmium, nickel, and lead, with nickel concentrations notably higher than other metals. Furthermore, acidity under different treatments showed no significant differences, aligning with Awal (2014), who suggested that the absence of significant differences between plots for most parameters (except pH) may be due to minor variations over relatively small distances or specific plot selection. Analysis of SOC content revealed the highest amount under severe dieback, consistent with Duke et al. (2003). Under dieback treatments, carbon stocks increased due to adding dead branches to the soil and reducing CO_2 emissions from anaerobic sediment. Krauss et al. (2018) indicated that sediment desiccation resulting from mangrove forest mortality prevents oxidation of the sediment profile through continuous tidal inundation. However, over longer timescales, a gradual reduction in carbon outflow from dead mangrove forests is expected, as soil carbon stocks will be depleted through oceanic outflow (Sippo et al., 2019).

Analysis of chlorophyll a, b, and total chlorophyll contents under dieback and control treatments indicates that dieback negatively impacts their concentrations, with decreases correlating to dieback intensity. While no significant difference was observed in carotenoid concentrations under various treatments, carotenoid concentration was higher under severe dieback and other dieback treatments compared with control. Dieback in mangrove forests directly affects photosynthesis due to reduced leaf area (Agrios, 2005; Aeby and Santavy, 2006), leading to a reduction in average leaf lifespan (Reef et al., 2010). Several factors including disease, grazing, and cutting contribute to reduction in photosynthetic tissue, which in turn triggers dieback events in grey mangrove trees (Campbell et al., 2014; Lewis III et al., 2016; Rossi et al., 2020). All these factors collectively point to a pollution source in grey mangrove forests. The proximity of these forests to Sirik Port has created a potential source for pollution such as heavy metals, which subsequently impacts forest survival. Dittman et al. (2022) also confirmed that proximity of mangrove forests to pollution sources contributed to their dieback.

5 Conclusions

In this study, the proximity of the study area to the pollution source, Sirik Port, emerges as the most significant factor driving dieback of grey mangrove forests within Khor-e-Azini Province, Iran. The findings revealed that sediment erosion and heavy metal accumulation have escalated to hazardous levels, directly contributing to grey mangrove forest dieback. As dieback intensifies, physiological, vegetative, and plant production characteristics experience marked decline. The plant’ s reproductive capacity also diminishes, impacting overall health and vigor. These multifaceted challenges render grey mangrove forests vulnerable to harsh environmental and human-induced stresses, preventing effective self-repair. Consequently, these factors cumulatively lead to plant mortality and exacerbate dieback in this area. As a solution, it is strongly recommended to institute comprehensive management plans to rejuvenate severely affected areas.

Conflict of interest: The authors declare that they have no conflict of interest.

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Note: Figure translations are in progress. See original paper for figures.