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Artificially remediated plants impact soil physiochemical properties along the riparian zones of the three gorges dam in China

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River ecosystem biodiversity and biogeochemical processes are shaped largely by riverside vegetation and soil. Moreover, river ecosystems provide ecological services influenced by the surrounding vegetation and soil interactions. However, the mechanisms by which artificially remediated plants (ARPs) and riparian soil interact to provide these benefits are still unclear among various ARPs. This study fills this gap and examines the impact of ARPs along the riparian zones of Three Gorges Dam (TGD) in Chongqing City, China. We sampled four varieties of ARPs from the Ruxi River Basin in the TGD. These varieties included *Cynodon dactylon*, *Hemarthria altissima*, *Taxodium disticum*, and *Salix mastudana*. Our results indicated substantial changes in soil physicochemical parameters. Comparably, *T. distigum* contains significantly higher soil chemical contents. Interestingly, principal component analysis explained almost 100% of the variance for all plant species in this study. Moreover, different vegetation types and soil chemical properties were positively correlated using Pearson correlation analysis ($p < 0.05$). Furthermore, all plant species exhibited strong negative correlations with physical characteristics (up to $r = -1.00$). Specifically, these mechanisms explain the interactions between ARPs and soil from riparian areas in the TGD. Hence, this study may facilitate ecological restoration and land management in degraded riparian areas.

KEYWORDS

river ecosystem, riparian soil, riparian vegetation, *Cynodon dactylon*, *Hemarthria altissima*, *Taxodium disticum*, *Salix mastudana*

1 Introduction

Riparian areas play a crucial role as vital connectors between hillsides and water channels, making them paramount for the conservation of aquatic ecosystems (Cory et al., 2023; Arif et al., 2024). They serve as unique settings for rich biological interactions between land and water environments (Bhatt, 2022; Chen et al., 2022). However, these systems are also vulnerable to modifications induced by human activities (Hira et al., 2023), such as deforestation, soil alteration, and the adoption of various farming techniques (Bhatt, 2022; Fiorillo et al., 2022). These zones have been extensively utilized in recent decades, resulting in deterioration of water quality, increased soil erosion, depletion of nitrogen, and an increase in saline content (Adla et al., 2022). The vital functions of these zones are threatened (Said and Misana, 2022). Soils and vegetation in riparian zones are essential elements in river ecosystems, impacting biodiversity and environmental chemistry (Majumdar and Avishek, 2023; Zheng et al., 2023). Within these zones, the development of specific vegetation types is crucial for maintaining ecological balance, stabilizing the surrounding land, and enhancing crop productivity and species diversity (Moore et al., 2023; Narayanan and Ma, 2023). It is imperative to acknowledge that the effectiveness of interventions based on vegetation may vary significantly based on the intricacies and fluctuations of the nearby ecosystems (Rauf et al., 2023). Thus, even though certain plants can reduce soil erosion, enhance soil stability, and provide food and shelter to a variety of animal species (Cotas et al., 2023; Rathod et al., 2023), it is essential to conduct comprehensive ecological impact assessments to fully comprehend their potential consequences. This approach helps in recognizing and mitigating hazards, especially in areas with delicate or already stressed ecosystems, such as competition with nearby plants or habitat change. The soil characteristics in these regions influence numerous biological processes, including the breakdown of organic matter, carbon storage, and nitrogen changes (González Giro et al., 2023; Omoarelojie and van Staden, 2023). To ensure that the introduction or promotion of specific plant species does not unintentionally result in ecological imbalances, it is essential to recognize these dynamics. Given this, several soil properties are crucial for sustainable development and can serve as markers to assess how well management approaches aimed at reviving soils and ecosystems are working (Wang and Delavar, 2023; Yusof et al., 2023).

Riparian vegetation is integral to nutrient distribution and availability (Bita-Nicolae, 2023). Similarly, the growth and succession of riparian vegetation are greatly influenced by soil and other environmental conditions. Moreover, riparian vegetation impacts the dispersion, aggregation, sedimentation, moisture content, and size of soil particles (Crimaldi and Lama, 2021; Aparício et al., 2023; Ray et al., 2023). Congruently, landscape ecology recognizes the importance of riparian vegetation as a filter, capturing sediment and nutrients as they move through the watershed (Nakamura, 2022). It has been demonstrated that dense plant growth improves surface roughness, which slows runoff and allows water infiltration into the soil (Zhu et al., 2020). It not only reduces soil erosion but also reduces particulate matter entering rivers, including soil particles and associated pollutants. It has been proven that riparian vegetation contributes to healthy aquatic ecosystems by improving water quality (Nsenga Kumwimba et al., 2023). Furthermore, changes in soil chemical properties may further impact riparian vegetation's health and function. In artificially remediated plant (ARP) soils, a diverse range of vegetation, including species such as *Cynodon dactylon*, *Salix matsudana*, *Taxodium disticum*, and *Hemarthria altissima*, contributes to the filtration of the landscape. The capacity to retain soil structure and collect particles varies across these species. However, it is essential to recognize the possibility of uneven or even detrimental effects in delicate areas, like the Three Gorges Dam (TGD) area. Due to their varying capacities, these vegetation types require extensive ecological evaluations, ongoing monitoring, and the application of adaptive management techniques in ARPs. These procedures are necessary to prevent negative effects on the environment and local biodiversity by properly comprehending and managing ecological interactions and their long-term implications. This strategic approach is essential to ensuring that ARP makes a positive contribution to ecological balance and sustainability, especially in areas impacted by major infrastructure projects like the TGD.

It is certainly clear that ARP soil has several effects on physical properties, including soil temperature, oxidation reduction potential, bulk density, and water content (Olagoke et al., 2022; Singh et al., 2022; Zanli et al., 2022; Shahbaz et al., 2023). Microbial activity is dependent on soil temperature, and remediation techniques that incorporate organic matter can moderate soil temperatures, thereby influencing biological processes (Aparicio et al., 2022). For instance, biochar supports microbial communities (Hamidzadeh et al., 2023). Similarly, the oxidation reduction potential can also be changed through remediation (Shen et al., 2022). The importance of understanding and manipulating this aspect of plant growth has been demonstrated by Bhattacharjee et al. (2022). Soil bulk density reflects both its compaction and its pore space, and it has been shown that ARP soils have reduced bulk density, thereby promoting root penetration and aeration (Guerin, 2022). However, missteps in remediation can increase bulk density, restricting growth (Piccoli et al., 2022). Improvements in soil water content are crucial in arid regions and have been achieved through organic matter amendments that boost the soil's water-holding capacity (de Jesus Duarte et al., 2022). Moreover, bulk density changes may influence both soil water composition and oxidation retention potential (Falkenberg et al., 2023), which highlights the importance of a comprehensive understanding of these interactions. Ultimately, the impact of ARP soil on specific physical properties is complex and carries significant implications for environmental protection. Implementing remediation techniques with care and knowledge is essential to maximizing benefits and minimizing unintended consequences (Lama et al., 2020a; Pirone et al., 2022). Although existing research provides strong guidance, further exploration is necessary to fully exploit soil remediation potential across ecological contexts.

The chemical characteristics of ARP are influenced by a wide range of parameters, such as soil pH, organic matter, accessible potassium, carbon, nitrogen, and phosphorus. Thorough examination of each of these aspects is crucial (Feng et al., 2022). While pH significantly impacts microbial activity and nutrient availability, it is important to consider the broader implications when applying sulfur or lime compounds to remediate soil. According to Tan et al. (2022), these methods can alter soil pH to benefit crops, but they may also result in intricate interactions within the soil ecosystem that could have long-term negative repercussions. For example, adding lime to acidic soils can increase nutrient availability (Hammerschmitt et al., 2021), but site-specific assessments are necessary to fully comprehend and control these interactions. Similarly, the risk of unforeseen environmental imbalances or a decline in soil biodiversity due to these adjustments must be weighed against the importance of soil organic matter (SOM) in preserving plant nutrition and sustaining soil structure. To ensure that changes in soil pH do not unintentionally compromise the ecological integrity of the soil and that agricultural productivity is harmoniously balanced with environmental conservation, practical approach places a heavy emphasis on long-term monitoring and adaptive management strategies. Researchers have extensively investigated the benefits of organic matter incorporation, demonstrating that it increases cation exchange capacity (Joseph et al., 2021) and water-holding capacity (Lama et al., 2020b; Tuozzo et al., 2022). Similarly, potassium in the soil is essential for plant growth. In addition, remediation techniques that rely on potassium supplementation have been found to significantly increase potassium availability and total potassium, thus supporting diverse physiological processes in plants (Akbar et al., 2023). Furthermore, the systematic addition of specific minerals or organic matter enhances phosphorus availability, which plays an integral role in essential plant functions such as energy exchange (Prasad et al., 2021). Soil fertility is directly related to carbon and nitrogen levels. It is well known that synthetic remediation, especially through organic amendments such as compost or manure, increases total carbon and nitrogen, thereby fostering the growth of microbes and the cycle of nutrients (Li C. et al., 2021; Li X. et al., 2021). Various remediation techniques can also affect total phosphorus, which includes both organic and inorganic forms and has direct impacts on long-term soil fertility (Maharajan et al., 2021).

A balanced and thorough strategy for remediation is essential due to synergistic interactions among soil chemical characteristics, such as the influence of soil pH on the availability of phosphorus and other nutrients (Wang et al., 2019). Understanding the intricate relationships that exist between various soil constituents, nutrients like potassium and nitrogen, and organic matter is crucial, especially in situations where environmental sustainability is a concern (Nisa et al., 2021). Ultimately, the impacts of ARP soils on chemical properties represent relevant and complex areas of study with direct implications for environmental sustainability. Science-based strategies for modifying soil pH, SOM, potassium, carbon, nitrogen, and phosphorus can enhance soil productivity and soil restoration (Lal, 2004). However, the nuanced interplay between these chemical properties demands a precise, context-specific approach, considering both short-term goals and long-term ecosystem balance. As soil remediation techniques are tailored to specific regions soil types and ecological conditions, continued research and innovation will be essential to harnessing their full potential. Furthermore, ecological services will be maintained. Predicting the evolution of ecosystems critically depends on understanding the complex dynamics of nutrient cycles in riparian soils and how those cycles affect environmental conditions (Padulano et al., 2020). The current investigation focuses on three objectives: Firstly, it illustrates changes in soil physicochemical properties under different riparian ARP types. Secondly, it aims to determine the relationships between soil physical and chemical properties. Lastly, it reveals the influence of soil physical and chemical properties on riparian soil properties under ARP types. Understanding these relationships serves as a vital step in managing and preserving multifaceted interactions within aquatic and terrestrial ecosystems. This ensures ecological stability and resilience.

2 Materials and methods

2.1 Research area overview

The research was conducted in the Ruxi River Basin, part of Zhongxian County within Chongqing City, China (coordinates 107°32–108°14′E, 30°03–30°35 N). The Ruxi River, which is a tributary of the Yangtze River in TGD, is located in Zhongxian County. Nearby, Shibao Town is situated to the northeast of Zhongxian County, adjacent to the Yangtze River's north bank (see Figure 1). The climate falls within the subtropical southeast monsoon zone (Arif et al., 2023), with an annual mean temperature of 18.2°C and a contrasting average yearly low of 10°C. The daily illumination stands at 29%, and the total annual illumination is 1327.5 h, while solar radiation measures 3.5×10^5 $J{\cdot}cm^{-2}$. The area receives 1,200 mm of rain annually, maintaining a relative humidity of 80%. The landscape is dominated by calcareous purple soil, characterized by minimal degradation and maturation. However, it is marked by noticeable water movement and soil erosion phenomena.

2.2 Field investigation

The academic research group based in Chongqing started this field study in the riparian area of the TGD in spring 2012. More precisely, this research took place in Shibao Town. This experiment focused on four plant species: *Cynodon dactylon*, *Hemarthria altissima*, *Taxodium disticum*, and *Salix matsudana*. Although these plants have been inundated for eight consecutive years (e.g., 2012–2020), they have maintained appropriate growth conditions. The research data collected in the study area for this study adopted an intricate sampling regime across three distinct time periods: early spring May 2020 (T1), July 2020 (T2), and September 2020 (T3). Within each of these timeframes, sampling employed two S-shaped transects in the riparian zone to ensure a comprehensive representation of the study area. In each S-shaped transect, three 1 m × 1 m quadrats were randomly placed at a distance of more than 10 meters between each sample. Thereby providing an additional layer of randomization. Within each quadrat, five soil blocks—each measuring 15 cm × 15 cm × 20 cm—were placed in a quincunx pattern.

For all four plant species, 45 samples from the rhizosphere and another 45 from the non-rhizosphere were gathered within the transect, resulting in 90 samples per species. In total, 360 soil samples were collected during the study. This methodical sampling strategy, from the design of the S-shaped transect to the quincunx arrangement of soil blocks, was meticulously crafted to derive scientifically sound conclusions. Such meticulous methodological planning is aimed at fulfilling the high standards of statistical power and reliability expected in scholarly research. Samples were collected at a soil depth of 0 to 20 cm, avoiding any obstructions like stones or roots. Subsequent to their collection, these soil samples were amalgamated for each quadrat and air-dried in a laboratory setting to facilitate subsequent physicochemical analyses.

2.3 Laboratory analysis

As part of the investigation, the quartering technique was diligently applied to the mixed soil sample to finely grind and sieve it in order to remove any visible stones, roots, or remnants of plants. This study examined soil physicochemical properties in detail, including measurements of soil temperature (ST), oxidation–reduction potential (ORP), bulk density (BD), soil water content (SWC), soil pH, SOM, available potassium (AK), whole potassium (WK), total carbon (TC), total nitrogen (TN), available phosphorous (AP), and total phosphorus (TP).

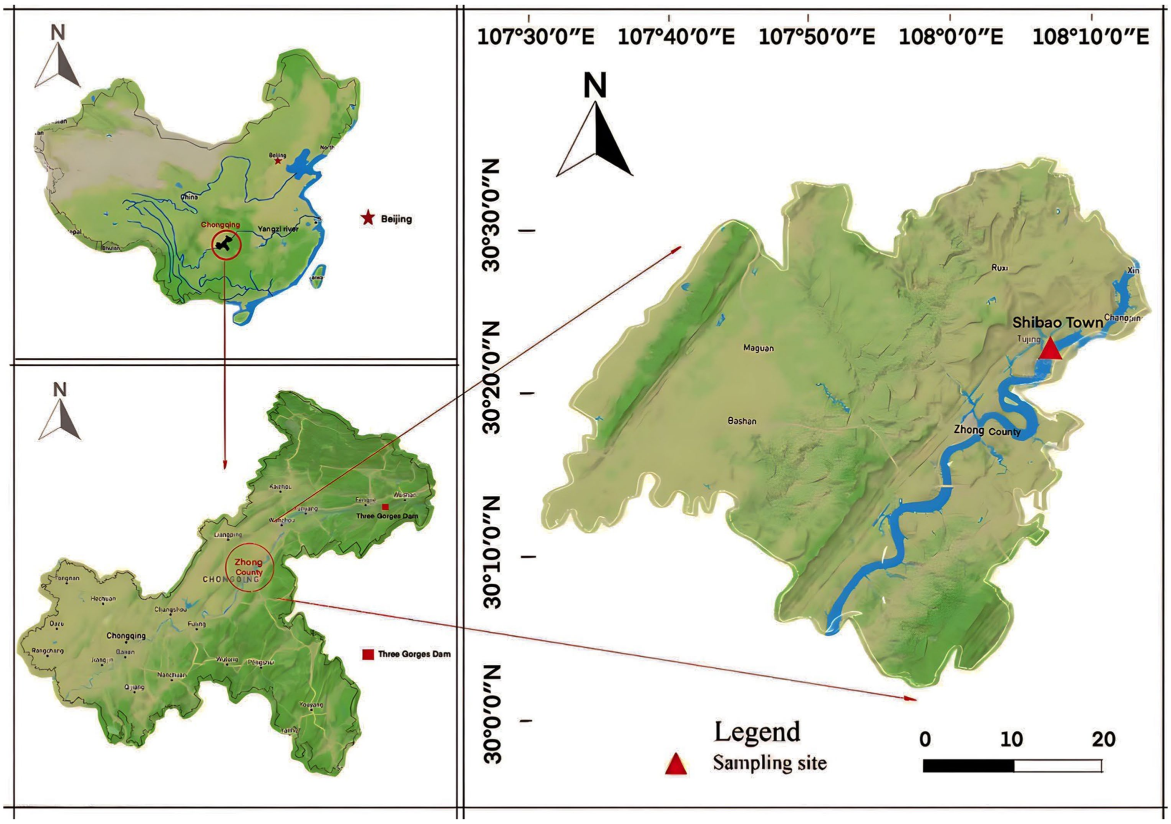

FIGURE 1
Location of the study area and sample site within the Three Gorges Dam (TGD) in China.

We employed redox potentiometers to determine ST and ORP, providing insights into the soil's electrochemical state. Additionally, the oven-drying method was utilized to determine BD and SWC, followed by the volumetric ring knife method after drying samples at 105°C for 24 h until a stable mass was achieved. BD was then calculated by comparing the oven-dried undisturbed core weight ratio to the cutting ring volume, providing information regarding the physical structure of the soil (Muscetta et al., 2023).

The pH of the soil was determined using electrode potentiometry, an essential factor in assessing soil fertility. We used a colorimetric approach to analyze SOM using potassium dichromate. A sensitive method for detecting AK and WK was used to determine the quantities of these elements by inductively coupled plasma emission spectroscopy. In order to determine the content of TC and TN, we employed an elemental analyzer (Elementar Vario EL, Germany), which is a sophisticated, high-resolution instrument that facilitates accurate measurement. Finally, molybdenum-antimony antichromatic analysis was used to determine the phosphorus content of AP and TP. In addition to their rigorous nature, these methods and procedures demonstrate a thorough and methodical approach to the understanding of the multifaceted soil composition, thereby providing the foundation for future ecological investigations.

2.4 Statistical analysis

An analysis of variance (ANOVA) was utilized to determine whether there were any differences in soil physical and chemical properties. In addition to this method, a two-tailed, unpaired test was used to determine the statistical significance, which permitted a deeper understanding of the underlying variations. The Pearson correlation coefficient, which was calculated using Origin software, provided an analytical perspective on the interactions between the multifaceted physical and chemical characteristics of soil along ARPs. This study used *t*-tests to discern pairwise differences among various soil chemical properties across distinct vegetation types. These properties encompass a range of metrics, namely PH, SOM, AK, WK, TC, TN, AP, and TP. Such pairwise comparisons are pivotal in understanding how different vegetation types might influence or be influenced by the underlying soil chemistry. The use of *t*-tests and the subsequent graphical representation via box plots were meticulously designed to offer a comprehensive, yet accessible, overview of soil chemical properties across different vegetation types in the specified region. The inclusion of significance markers further reinforces the academic rigor and validity of the presented findings.

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As well, principal component analysis (PCA) was employed with the same analytical tool in order to explore the interrelationships between an array of soil physical and chemical factors along ARPs, including ST, ORP, BD, SWC, soil pH, SOM, AK, WK, TC, TN, AP, and TP. This sophisticated analytical approach provided an extensive understanding of the complex dynamics prevailing within soil composition. This study provides new insights into intricate interactions and correlations that are not only academically valuable, but also have potential practical applications in ecological research, environmental preservation, and strategic land management.

3 Results

3.1 Riparian soil physical properties under different vegetation types

Figure 2 illustrates the physical properties of the soil under different vegetation types using the box plot method. There was a variation in SWC between 17 and 26% (Figure 2D). The ST value was higher in *Cynodon dactylon* and lower in *Hemarthria altissima* (Figure 1A). *Cynodon dactylon* showed the lowest BD, and *Salix mastudana* showed the highest BD (Figure 2C). It was found that *Taxodium disticum* had a higher ORP (Figure 2B). Despite this, we found no significant difference between the four vegetation types in terms of physical properties.

3.2 Riparian soil chemical properties under different vegetation types

Figure 3 depicts the soil chemical properties using box-normal plots under different vegetation types. AK, TC, TN, and TP were found in high abundance in *Taxodium disticum* and in lower quantities in *Salix mastudana* ($p < 0.05$) (Figures 3C,E,F,H). *Salix mastudana* had the highest soil pH ($p < 0.05$), whereas *Cynodon dactylon* had the lowest (Figure 3A). It was found that *Salix mastudana* had the lowest SOM and WK ($p < 0.05$) (Figures 3B,D). *Hemarthria altissima* had the highest AP content, while the other three vegetations gradually reduced it (Figure 3G).

3.3 Relationships between riparian soil physical and chemical properties

We performed Pearson correlation coefficient analyses on the different chemical and physical characteristics of the soil using significance levels of $p < 0.001$***, $p < 0.01$**, and $p < 0.05$*. The pH,

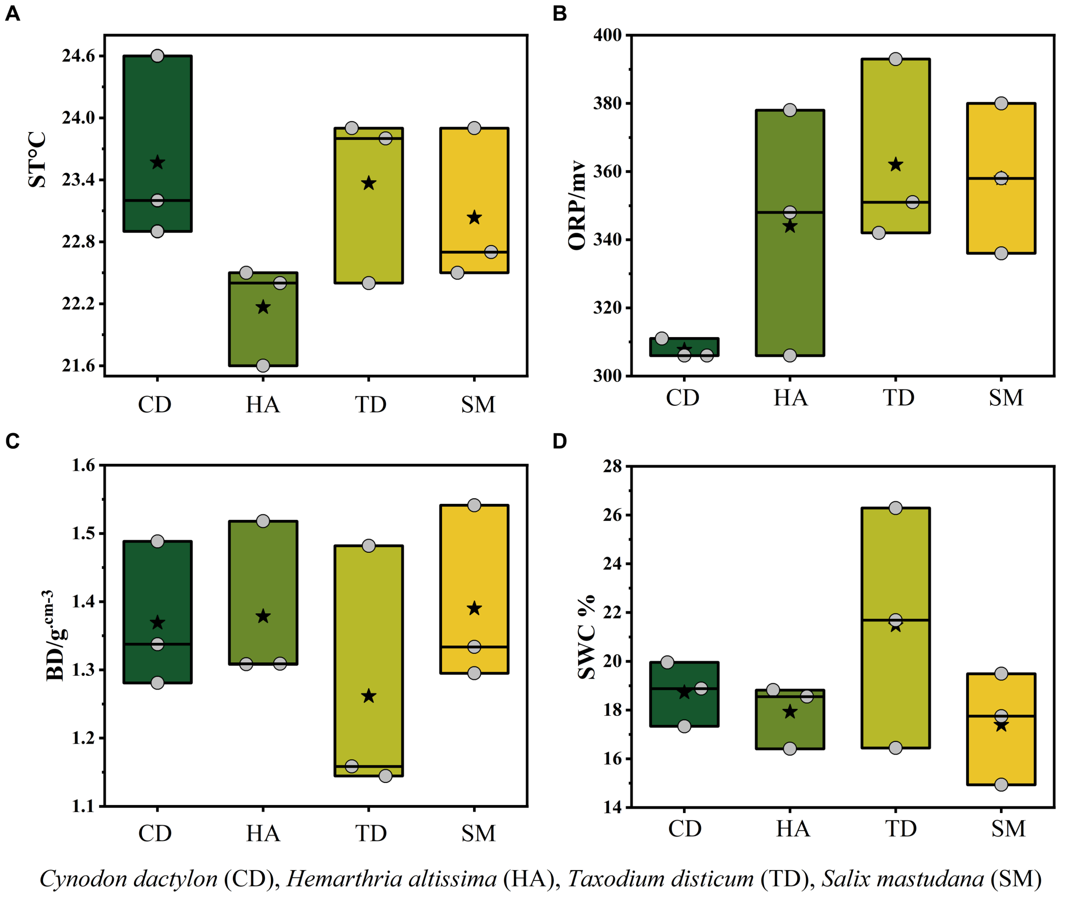

FIGURE 2
Box plots **(A–D)** of the soil's physical properties under different vegetation types along the riparian zone of the TGD in China. Abbreviations in the figure define soil temperature (ST), oxidation-reduction potential (ORP), bulk density (BD), and soil water content (SWC).

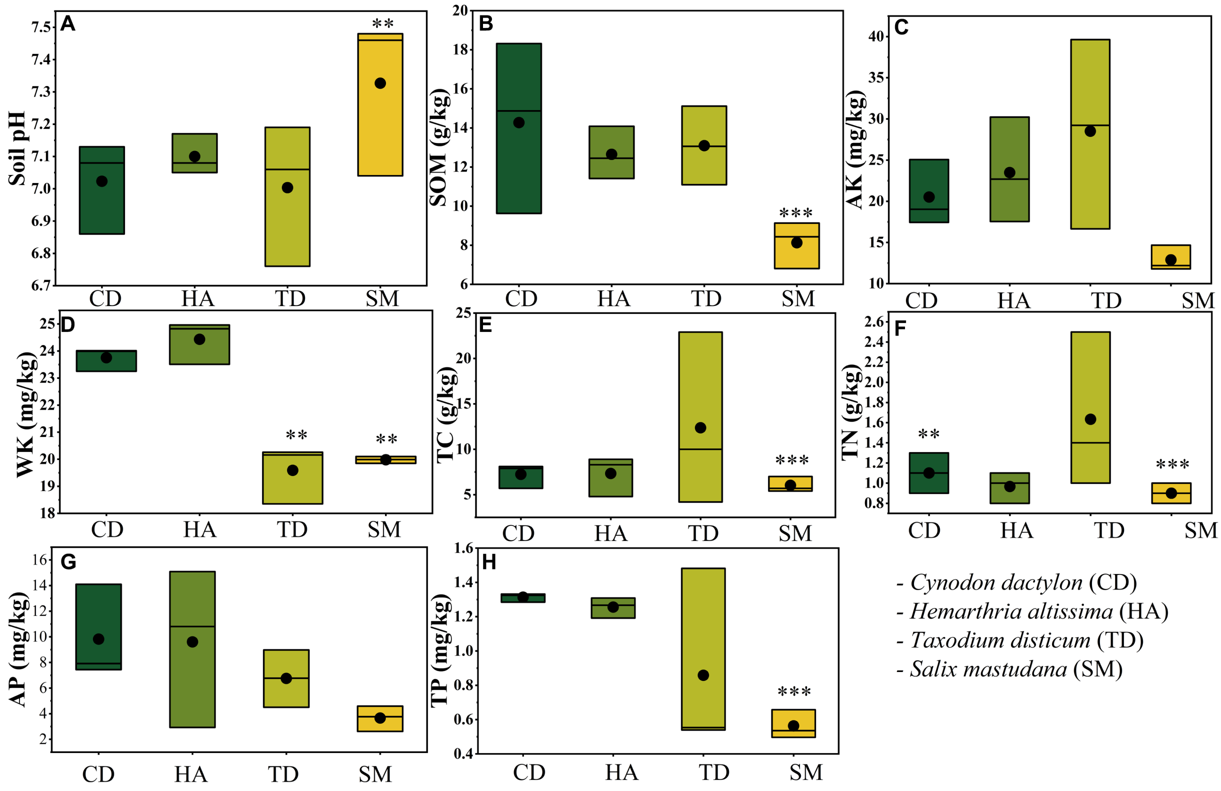

FIGURE 3
Box plots **(A–H)** of the soil's chemical properties under different vegetation types along the riparian zone of the TGD in China. Abbreviations in the figure define pH values (PH), soil organic matter (SOM), available potassium (AK), whole potassium (WK), total carbon (TC), total nitrogen (TN), available phosphorous (AP), and total phosphorous (TP). Note: * indicates significant differences at $p < 0.01$ (**) or $p < 0.001$ (***) according to the paired *t*-tests.

SOM, AK, and AP in soil were significantly correlated negatively with ST, ORP, and BD in *Hemarthria altissima*, i.e., ($r \leq -1.00^{***}$). Figure 4A illustrates this. There was a significant negative correlation between *Cynodon dactylon* physical properties ($r \leq -1.00^{***}$). This is presented in Figure 4B. *Taxodium disticum* and *Salix mastudana* show mixed but strong negative correlations with physical properties ($r \leq -1.00^{***}$). Figures 4C,D depict this phenomenon.

3.4 Response of riparian soil physical and chemical properties to different vegetation types

PCA was used to determine how riparian soil properties responded to different vegetation types in Figure 5. It can be concluded that axes 1 and 2 of the PCA account for almost 100% of the variance in the data. We found that PC1 of *Cynodon dactylon* was strongly correlated with soil pH, WK, TP, and SWC. Meanwhile, PC2 exhibits a strong positive association with TN and ST as well as a negative association with SOM (Figure 5A). PC1 of *Hemarthria altissima* showed a strong positive association with SOM and a negative association with ORP, whereas PC2 showed a strong positive association with AK, WK, and TP (Figure 5B). A strong positive association was observed between PC1 of *Taxodium disticum* and TC and ST, whereas negative relationships were observed with TP, ORP, and BD. Conversely, PC2 has a stronger positive relationship with WK and TN (Figure 5C). TP and SWC were positively associated with PC1 of *Salix mastudana*, while TN and ORP were negatively associated. In contrast, PC2 has a stronger positive correlation with AK and BD (Figure 5D).

4 Discussion

ARPs contribute significantly to soil and water resource conservation. Its efficiency depends on vegetation type and density (Siqueira et al., 2021). Studies have shown that dense vegetation intercepts and traps unwanted materials (Opitz et al., 2021). In contrast, areas with less vegetation are more likely to experience erosion (Wu et al., 2020), which occurs when soil is worn away over time. Degradation of soil can lead to a more rapid loss of soil particles, which can have adverse effects on the soil (Liu L. et al., 2020; Liu Y. F. et al., 2020). As we examine specific examples (ARPs), we can observe significant differences in their abilities to maintain soil structure and intercept particulates. Although various types of vegetation can contribute to soil conservation, their structural characteristics may result in varying degrees of effectiveness. The dense growth characteristic of *Cynodon dactylon* may mean it is more capable of robust interception (Tu et al., 2021). Alternatively, *Salix matsudana* may have different properties that affect its soil conservation ability. This study shows that nutrient levels, pH, and organic matter content differ significantly among various vegetation

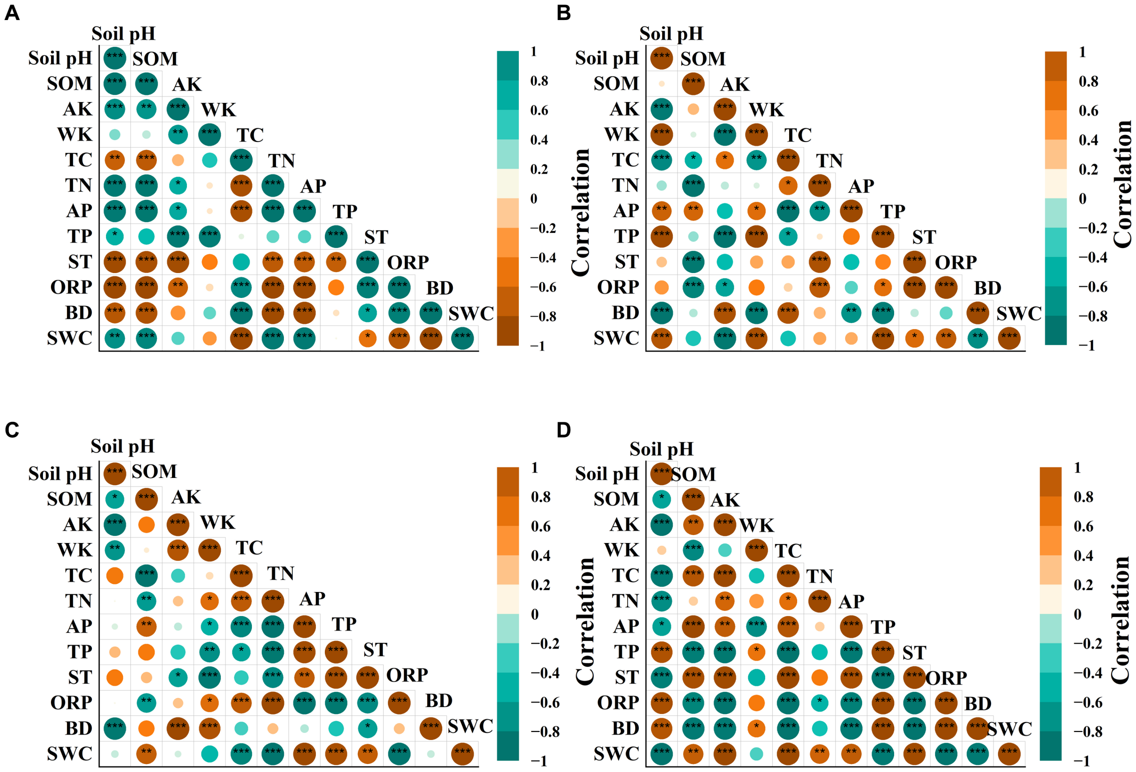

FIGURE 4
Heat maps of Pearson's correlation coefficient analysis between soil physicochemical properties under different vegetation types [*Hemarthria altissima* **(A)**, *Cynodon dactylon* **(B)**, *Salix mastudana* **(C)**, and *Taxodium disticum* **(D)**] along the riparian zones of the TGD in China. ***Correlation is significant at the 0.001 level; **Correlation is significant at the 0.01 level; *Correlation is significant at the 0.05 level. Abbreviations in the figure are defined as pH values (PH), soil organic matter (SOM), available potassium (AK), whole potassium (WK), total carbon (TC), total nitrogen (TN), available phosphorous (AP), total phosphorous (TP), soil temperature (ST °C), oxidation–reduction potential (ORP), bulk density (BD), and soil water content (SWC).

types. Previous studies have also explored nutrient variation across soil types (Gao et al., 2023) and the factors underlying these variations (Ghani et al., 2023; Proto and Courtney, 2023). This study contributes to the existing literature by clarifying the relationship between ARPs and soil properties. Vegetation affects soil carbon and nitrogen, but no significant differences were found between the four ARPs (Figure 2). Variability is complex, influenced by many factors including slope, soil texture, and hydrological processes, and is related to soil nutrients' higher mobility (Alves, 2023). Landscapes adjacent to the sampling site may also influence nutrient content. The results indicate that the interaction between ARPs and soil nutrients is multifaceted and not solely determined by vegetation type (Meng et al., 2023). To accurately assess riparian ARP's ability to retain nutrients, it is necessary to consider various environmental and site-specific factors.

Potassium availability variation across different soil types has been well documented (Bilias et al., 2023; Doulgeris et al., 2023; Gowthamchand et al., 2023; Yan et al., 2023). *Salix mastudana*'s soil has the lowest potassium levels available, which is consistent with Wu et al. (2023), who observed a reduced potassium availability in certain soil types. In an attempt to explain such variations in potassium availability, Lee et al. (2011) demonstrated that the soil mineral composition and texture may be responsible. Fernandez et al. (2023) found that specific vegetation can enhance potassium availability in *Hemarthria altissima* soil, as evidenced by Figure 3G. Various studies have supported this concept, for example those by Hailing et al. (2020), who found that certain soil microbial communities associated with particular plant species may enhance potassium mineralization. In addition, the interaction between plant roots and soil potassium has been the subject of research. This provides insight into how different plants affect soil nutrients. Researchers Rafique et al. (2019) and Zhong et al. (2020) have found that specific root exudates may influence soil potassium availability. Our study aligns with a series of earlier studies (Stumpf et al., 2022; Ye et al., 2022; Li et al., 2023a) that investigated potassium levels in various soil types. Plant species and soil nutrient content are discussed in more detail for four ARPs.

The recent findings regarding the total carbon, nitrogen, and phosphorus contents of soil types contribute to an expanding body of knowledge in the field of ecology. Results of our study revealed that the content of TC, TN, and TP was higher in *Taxodium disticum* and the lowest in *Salix mastudana* (Figures 3C,E,F,H). The soil pH was highest in *Salix mastudana* and lowest in *Cynodon dactylon* (Figure 3A), which supports previous findings and extends our understanding of the complex relationship between vegetation types and soil nutrients. First, the alignment with Liu L. et al. (2020) and Liu Y. F. et al. (2020) further supports the notion that soil nutrients are correlated with vegetation types. Makoto and Koike (2021) have reached similar conclusions, emphasizing the fact that specific vegetation types have a significant impact on nutrient cycles within soil ecosystems. Observations made by Li et al. (2023a,b) indicate that certain tree species may prefer soils rich nutrients as a way of adapting

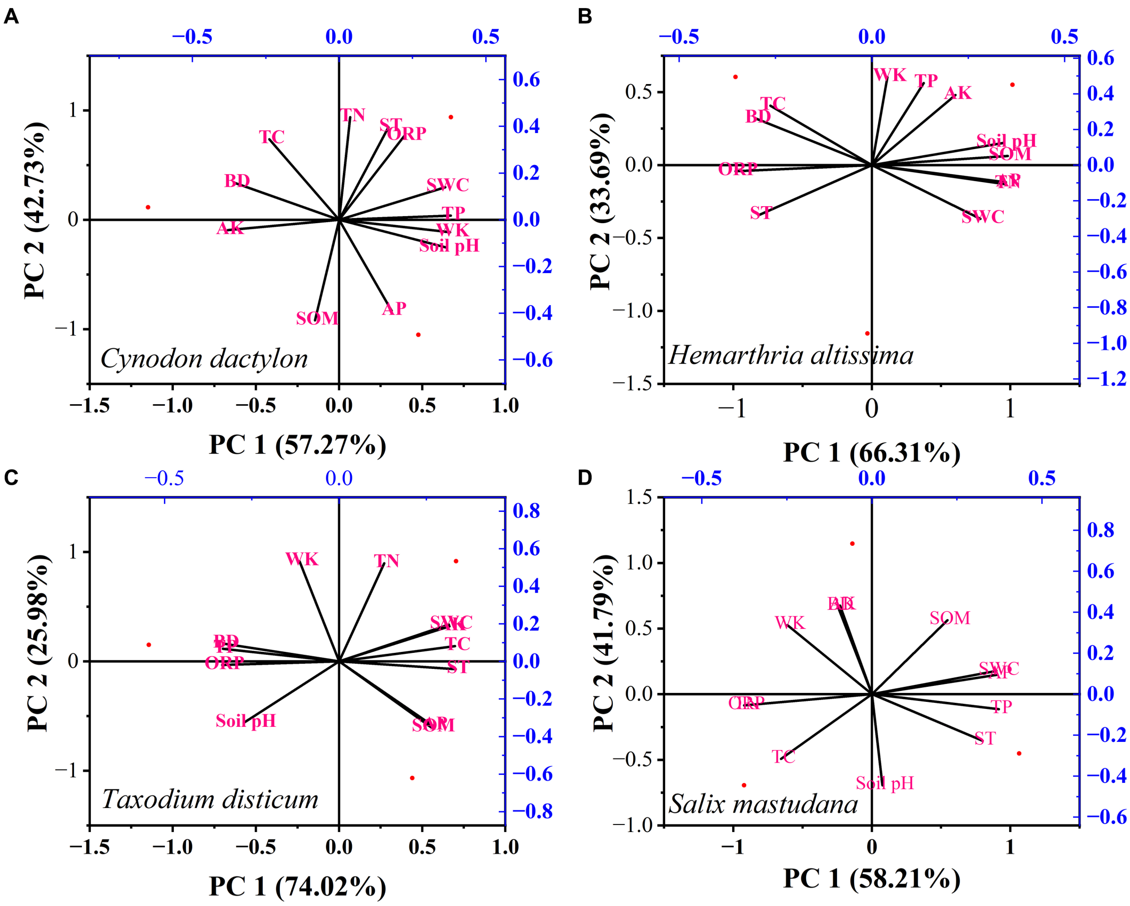

FIGURE 5

Principal component analysis of soil physicochemical properties under different vegetation types [*Cynodon dactylon* **(A)**, *Hemarthria altissima* **(B)**, *Taxodium disticum* **(C)**, and *Salix mastudana* **(D)**] along the riparian zones of TGD in China. PCA axes 1 and 2-factor loadings explained almost 100% of the total variance. Abbreviations in the figure are defined as pH values (PH), soil organic matter (SOM), available potassium (AK), whole potassium (WK), total carbon (TC), total nitrogen (TN), available phosphorous (AP), total phosphorous (TP), soil temperature (ST °C), oxidation–reduction potential (ORP), bulk density (BD), and soil water content (SWC).

to their niche. Guo et al. (2023) reached similar conclusions by observing that certain trees might enhance soil fertility through biological nitrogen fixation. Moreover, studies focusing on mycorrhizal relationships have further elucidated the relationship between soil types and total nutrient content. Landscape ecology has examined the spatial variability of soil nutrients, including carbon, nitrogen, and phosphorus (Li C. et al., 2021; Li X. et al., 2021). Long et al. (2022) argue that topography, climate, and human activity can affect these variations. This multifaceted topic is further complicated by vegetation type, as noted in this study. The findings related to total carbon, nitrogen, and phosphorus in different soil types contribute to our understanding of soil-vegetation interactions. This study provides valuable insights into ecology, agronomy, and land management. It reaffirms the intricate and nuanced relationship between plant species and their environments.

The findings of this study concerning pH variations in soils and their relationship with specific plant species such as *Salix mastudana* and *Cynodon dactylon* extend existing knowledge in soil science and plant ecology. Previous research has demonstrated the significance of soil pH in determining plant distribution and growth (Msimbira and Smith, 2020; Kang et al., 2021; Ni et al., 2021). *Salix mastudana* soil exhibits a greater pH, which is consistent with Han et al. (2022), who conclude that some plants may increase soil alkalinity. Penn and Camberato (2019) highlighted how certain plants may release cations that increase soil pH because of ion exchange at the root surfaces. This phenomenon may be related to the ion exchange process that occurs at the root surface. Conversely, the lower pH found in *Cynodon dactylon* soil is consistent with Licata et al. (2022) findings. Several grasses, including *Cynodon dactylon*, thrive in acidic soils. Several researchers have explored the underlying mechanisms of soil pH variation, such as Mokgakane et al. (2021), who suggested that certain grass species might produce organic acids that decrease soil pH. PH fluctuations in soil also have broad ecological implications. Mahohi and Raiesi (2021) emphasized the importance of pH in soil microbial communities, including its impact on nutrient cycling. Additionally, Ni et al. (2020) demonstrate that pH can influence phosphorus and iron availability. It may be concluded that the present study's observations about pH variation in *Salix mastudana* and *Cynodon dactylon* soils agree with those reported in previously mentioned studies. These studies contribute to plant–soil interactions. By emphasizing the importance of plant species in modulating soil pH, these findings underscore the nuanced relationship between soil properties and vegetation. Researchers and practitioners will benefit from these insights in the broader fields.

Additionally, the findings of the current study regarding whole potassium and SOM levels agree with existing research. This illustrates the intricate relationship between ARPs and soil properties. Earlier research by Dang et al. (2021), Hu et al. (2022), Voltr et al. (2021), and Zhang et al. (2021) reinforced the observed relationships, emphasizing that different plant species affect soil potassium and SOM levels differently. Those relationships are integral to understanding soil biogeochemical cycling processes as well as having practical implications for land management (Jakšić et al., 2021). These results emphasize how vegetation influences soil properties and suggest that targeted vegetation management is an effective tool for manipulating soil properties in accordance with ecological objectives (Huylenbroeck et al., 2020). The study adds to the growing body of evidence demonstrating that soil and vegetation are interconnected in ecosystem dynamics. The variations in potassium levels, total nutrients, pH, and organic matter observed are consistent with current scientific understanding and provide nuanced insights into soil-vegetation interactions.

The present study reveals key insights into the relationships that govern soil ecology by analyzing correlations between different chemical and physical characteristics of soil. By using Pearson correlation coefficient analysis at different significance levels, negative correlations have been found within specific vegetation types, supporting existing research on soil–plant interactions (Figure 4). *Hemarthria altissima* exhibits significant negative correlations between soil pH, SOM, AK, and AP with ST, ORP, and BD, which are consistent with previous studies such as Matos et al. (2021). Several wetland grasses showed similar interactions between these properties, reflecting the plant's contribution to soil structure and nutrient cycling. The findings regarding *Cynodon dactylon*, which showed significant negative correlations with physical properties, agree with the findings by Kamchoom et al. (2022). It has been demonstrated that grass species such as *Cynodon dactylon* alter soil physical properties such as compaction, porosity, and bulk density. *Salix mastudana* and *Taxodium disticum* exhibit mixed but strong negative correlations with physical properties during their growth cycles. This is consistent with a broader understanding of how tree species impact soil attributes. Yang et al. (2023) demonstrated that certain tree species, especially in riparian zones, influence soil physical properties, influencing processes such as erosion and sedimentation. Several studies have concluded that Pearson correlation coefficient analysis is one of the most used methods for understanding complex relationships within environmental sciences, as outlined by Kumar and Chong (2018). Previous studies have demonstrated its utility in uncovering intricate relationships between various soil properties, including those conducted by Rendana et al. (2018).

The use of PCA to investigate the response of riparian soil properties to different vegetation types, as explored in this study (Figure 5), offers an insightful methodological approach to understanding the multidimensional nature of soil attributes. The association between principal components and soil properties under different vegetation types can be viewed within the context of previous literature. The strong positive association between PC1 and soil pH, WK, TP, and SWC of *Cynodon dactylon* supports our understanding of how certain grasses affect soil properties. It has been reported by Gao et al. (2020) that grass species alter the SWC and nutrient distribution, including phosphorus (TP). *Hemarthria altissima* was found to have associations with SOM, similar to previous studies like Fernandez et al. (2023). Several ecological studies have demonstrated that specific plant types are associated with nutrient cycling and organic matter dynamics in the soil (Odoh et al., 2020). Similarly, researchers such as Lamarque et al. (2023) have also observed relationships between TP, SWC, TN, and ORP for *Salix mastudana*. Salix species play a significant role in soil hydrology and nutrient dynamics. Additionally, methodological studies such as Abdel-Fattah et al. (2021) have emphasized PCA as a powerful tool for unraveling complex, multidimensional data. The effectiveness of this approach has also been demonstrated by Rangel-Peraza et al. (2017) in ecology and soil science.

5 Conclusion

This research offers profound insights that require further exploration. Through the examination of four varieties of ARPs, substantial changes in soil physicochemical parameters have been identified. Among these, *Taxodium disticum*'s soil exhibited higher levels of critical nutrients. This study unraveled the intricate relationship between different ARPs and soil's chemical properties through PCA. This accounted for almost 100% of the variance. Their correlations provide foundational information but reveal complexity in their interactions. In this regard, significant negative correlations with physical properties ($p<0.05$) also indicate that there may be underlying mechanisms or factors not yet fully understood. This research has implications beyond the study areas for similar ecosystems worldwide. The importance of understanding and mediating the effects of urbanization and industrialization on biodiversity and biogeochemical processes cannot be overstated, as these factors continue to pressure riparian environments. Future research should consider a comprehensive study of ARPs' effects on different soil types, employing longitudinal studies and diverse methods. Additionally, it is worthwhile to consider the possible negative impacts or unintended consequences of ARPs. These include disruptions to native ecosystems, changes in soil chemistry, or potential adverse effects on fauna in the surrounding area. Overall, this study provided valuable insights into the interaction between ARPs and riparian soils. However, it also exposes areas where our understanding is still evolving. The development of sustainable practices in land management and ecological restoration will undoubtedly benefit from a deeper, more comprehensive exploration of these interactions, which will ensure the preservation and revitalization of these crucial ecosystems.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

FN: Conceptualization, Data curation, Formal analysis, Methodology, Software, Visualization, Writing – original draft. MA: Conceptualization, Funding acquisition, Project administration, Resources, Software, Supervision, Visualization, Writing – original draft, Writing – review & editing. TX: Conceptualization, Data curation, Investigation, Methodology, Writing – original draft. CL: Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Abdel-Fattah, M. K., Mohamed, E. S., Wagdi, E. M., Shahin, S. A., Aldosari, A. A., Lasaponara, R., et al. (2021). Quantitative evaluation of soil quality using principal component analysis: the case study of El-Fayoum depression Egypt. *Sustainability* 13:1824. doi: 10.3390/su13041824

Adla, K., Dejan, K., Neira, D., and Dragana, Š. (2022). "Chapter 9—degradation of ecosystems and loss of ecosystem services" in *One health*. eds. J. C. Prata, A. I. Ribeiro and T. Rocha-Santos (Cambridge, Massachusetts, United States: Academic Press), 281–327.

Akbar, W. A., Rahim, H. U., Irfan, M., Alatalo, J. M., Mudasssir, M., and Bundschuh, J. (2023). Effects of incorporating pine-woodchip biochar with reduced NP fertilizer on calcareous soil characteristics, organic carbon, NPK availability, and maize productivity. *J. Soils Sediments* 24, 177–188. doi: 10.1007/s11368-023-03617-5

Alves, A. S. (2023). Soil, water and nutrient loss under simulated rainfall patterns in an area fertilised with chicken litter—Science direct. Available at: https://www.sciencedirect.com/science/article/abs/pii/S0022169423004857.

Aparício, B. A., Nunes, J. P., Bernard-Jannin, L., Dias, L. F., Fonseca, A., and Ferreira, T. (2023). Modelling the role of ground-true riparian vegetation for providing regulating services in a Mediterranean watershed. *Int. Soil Water Conserv. Res.* 11, 159–168. doi: 10.1016/j.iswcr.2022.07.005

Aparicio, J. D., Raimondo, E. E., Saez, J. M., Costa-Gutierrez, S. B., Álvarez, A., Benimeli, C. S., et al. (2022). The current approach to soil remediation: a review of physicochemical and biological technologies, and the potential of their strategic combination. *J. Environ. Chem. Eng.* 10:107141. doi: 10.1016/j.jece.2022.107141

Arif, M., Jie, Z., Behzad, H. M., and Changxiao, L. (2023). Assessing the impacts of ecotourism activities on riparian health indicators along the three gorges reservoir in China. *Ecol. Indic.* 155:111065. doi: 10.1016/j.ecolind.2023.111065

Arif, M., Petrosillo, I., and Changxiao, L. (2024). Effects of changing riparian topography on the decline of ecological indicators along the drawdown zones of long rivers in China. *Front. For. Glob. Change* 14:1293330. doi: 10.3389/ffgc.2024.1293330

Bhatt, R. P. (2022). "Impact on Forest and vegetation due to human interventions" in *Vegetation dynamics, changing ecosystems and human responsibility* (London, United Kingdom: Intech Open).

Bhattacharjee, R., Kumar, L., Mukerjee, N., Anand, U., Dhasmana, A., Preetam, S., et al. (2022). The emergence of metal oxide nanoparticles (NPs) as a phytomedicine: a two-facet role in plant growth, nano-toxicity and anti-phyto-microbial activity. *Biomed. Pharmacother.* 155:113658. doi: 10.1016/j.biopha.2022.113658

Bilias, F., Kalderis, D., Richardson, C., Barbayiannis, N., and Gasparatos, D. (2023). Biochar application as a soil potassium management strategy: a review. *Sci. Total Environ.* 858:159782. doi: 10.1016/j.scitotenv.2022.159782

Bita-Nicolae, C. (2023). Distribution of the riparian Salix communities in and around Romanian Carpathians. *Diversity* 15:397. doi: 10.3390/d15030397

Chen, Z., Song, H., Arif, M., and Changxiao, L. (2022). Effects of hydrological regime on *Taxodium ascendens* plant decomposition and nutrient dynamics in the three gorges reservoir riparian zone. *Front. Environ. Sci.* 10:990485. doi: 10.3389/fenvs.2022.990485

Cory, B. M., Smith, A., Deitch, M. J., Miller, D. L., Enloe, H., and Osborne, T. Z. (2023). Changes in ecosystem structure and composition influence groundwater chemistry in herbaceous wetlands. *Ecosystems* 26, 1603–1621. doi: 10.1007/s10021-023-00853-1

Cotas, J., Gomes, L., Pacheco, D., and Pereira, L. (2023). Ecosystem services provided by seaweeds. *Hydrobiology* 2:Article 1. doi: 10.3390/hydrobiology2010006

Crimaldi, M., and Lama, G. F. C. (2021). Impact of riparian plants biomass assessed by UAVAcquired multispectral images on the hydrodynamics of vegetated streams. European Biomass Conference and Exhibition Proceedings, 29th EUBCEOnline 2021, 1157–1161.

Dang, H., Zhang, T., Wang, Z., Li, G., Zhao, W., Lv, X., et al. (2021). Succession of endophytic fungi and arbuscular mycorrhizal fungi associated with the growth of plant and their correlation with secondary metabolites in the roots of plants. *BMC Plant Biol.* 21:165. doi: 10.1186/s12870-021-02942-6

de Jesus Duarte, S., Hubach, A., and Glaser, B. (2022). Soil water balance and wettability methods in soil treated with biochar and/or compost. *Carbon Res.* 1:31. doi: 10.1007/s44246-022-00032-2

Doulgeris, C., Kypritidou, Z., Kinigopoulou, V., and Hatzigiannakis, E. (2023). Simulation of potassium availability in the application of biochar in agricultural soil. *Agronomy* 13:784. doi: 10.3390/agronomy13030784

Falkenberg, R., Sigl, L., and Fochler, M. (2023). From 'making lists' to conducting 'well-rounded' studies: epistemic re-orientations in soil microbial ecology. *Soc. Stud. Sci.* doi: 10.1177/03063127231179700

Feng, H., Liang, Y. N., and Hu, X. (2022). Natural organic matter (NOM), an underexplored resource for environmental conservation and remediation. *Mater. Today Sustain.* 19:100159. doi: 10.1016/j.mtsust.2022.100159

Fernandez, M. B. D. G., Stumpf, L., Miguel, P., Pinto, L. F. S., Carlos, F. S., Schubert, R. N., et al. (2023). Biological quality and organic matter dynamics in minesoil at 18 years reclamation with perennial grasses. *Ecol. Eng.* 187:106866. doi: 10.1016/j.ecoleng.2022.106866

Fiorillo, D., De Paola, F., Ascione, G., and Giugni, M. (2022). Drainage systems optimization under climate change scenarios. *Water Resour. Manag.* 37, 2465–2482. doi: 10.1007/s11269-022-03187-0

Gao, J., Liu, D., Xu, Y., Chen, J., Yang, Y., Xia, D., et al. (2020). Effects of two types of activated carbon on the properties of vegetation concrete and *Cynodon dactylon* growth. *Sci. Rep.* 10:14483. doi: 10.1038/s41598-020-71440-w

Gao, L., Wang, W., Liao, X., Tan, X., Yue, J., Zhang, W., et al. (2023). Soil nutrients, enzyme activities, and bacterial communities in varied plant communities in karst rocky desertification regions in Wushan County, Southwest China. *Front. Microbiol.* 14:1180562. doi: 10.3389/fmicb.2023.1180562

Ghani, M. I., Wang, J., Li, P., Pathan, S. I., Sial, T. A., Datta, R., et al. (2023). Variations of soil organic carbon fractions in response to conservative vegetation successions on the loess plateau of China. *Int. Soil Water Conserv. Res.* 11, 561–571. doi: 10.1016/j.iswcr.2022.05.002

González Giro, Z., Pedraza Olivera, R., Lamadrid Mandado, R., Hu, J., Font Vila, L., Sleutel, S., et al. (2023). Invasive woody plants in the tropics: a delicate balance between control and harnessing potential benefits. A review. *Agron. Sustain. Dev.* 43:41. doi: 10.1007/s13593-023-00892-x

Gowthamchand, , Dhaliwal, S. S., Sharma, V., Verma, G., Singh, J., and Kaur, M. (2023). Variation of Physico-chemical properties among different soil orders under different land use Systems of the Majha Region in North-Western India. *Sustainability* 15:4779. doi: 10.3390/su15064779

Guerin, T. F. (2022). The effect of interactions between soil compaction and phenol contamination on plant growth characteristics: implications for scaling bioremediation at industrial sites. *J. Environ. Manag.* 302:114017. doi: 10.1016/j.jenvman.2021.114017

Guo, J., Xue, J., Hua, J., Yin, Y., Creech, D. L., and Han, J. (2023). Research status and trends of *Taxodium distichum*. *Hort Sci.* 58, 317–326. doi: 10.21273/HORTSCI17045-22

Hailing, L., Li, C.-X., Chen, C.-H., Yang, Z.-H., and Chen, X.-M. (2020). Root activities of re-vegetated plant species regulate soil nutrients and bacterial diversity in the riparian zone of the three gorges reservoir. *Huan jing ke xue= Huanjing kexue* 41, 2898–2907. doi: 10.13227/j.hjkx.201911214

Hamidzadeh, Z., Ghorbannezhad, P., Ketabchi, M. R., and Yeganeh, B. (2023). Biomass-derived biochar and its application in agriculture. *Fuel* 341:127701. doi: 10.1016/j.fuel.2023.127701

Hammerschmitt, R. K., Facco, D. B., Drescher, G. L., Mallmann, F. J. K., Ono, F. B., Zancanaro, L., et al. (2021). Limestone and gypsum reapplication in an oxisol under no-tillage promotes low soybean and corn yield increase under tropical conditions. *Soil Tillage Res.* 214:105165. doi: 10.1016/j.still.2021.105165

Han, X., Yu, M., Zhuo, R., Lu, Z., Li, S., Chen, J., et al. (2022). Lignin biosynthesis plays an important role on cadmium tolerance in *Salix Matsudana* VAR. Matsudana F. Umbraculifera Rehd (SSRN scholarly paper 4029274). doi: 10.2139/ssrn.4029274,

Hira, A., Arif, M., Nowsherwan, Z., Gul, Z., Xiangyue, L., and Yukun, C. (2023). Effects of riparian buffer and stream channel widths on ecological indicators in the upper and lower Indus River basins in Pakistan. *Front. Environ. Sci.* 11:1113482. doi: 10.3389/fenvs.2023.1113482

Hu, L., Li, Q., Yan, J., Liu, C., and Zhong, J. (2022). Vegetation restoration facilitates belowground microbial network complexity and recalcitrant soil organic carbon storage in Southwest China karst region. *Sci. Total Environ.* 820:153137. doi: 10.1016/j.scitotenv.2022.153137

Huylenbroeck, L., Laslier, M., Dufour, S., Georges, B., Lejeune, P., and Michez, A. (2020). Using remote sensing to characterize riparian vegetation: a review of available tools and perspectives for managers. *J. Environ. Manag.* 267:110652. doi: 10.1016/j.jenvman.2020.110652

Jakšić, S., Ninkov, J., Milić, S., Vasin, J., Živanov, M., Jakšić, D., et al. (2021). Influence of slope gradient and aspect on soil organic carbon content in the region of Niš, Serbia. *Sustainability* 13:8332. doi: 10.3390/su13158332

Joseph, S., Cowie, A. L., Van Zwieten, L., Bolan, N., Budai, A., Buss, W., et al. (2021). How biochar works, and when it doesn't: a review of mechanisms controlling soil and plant responses to biochar. *GCB Bioenergy* 13, 1731–1764. doi: 10.1111/gcbb.12885

Kamchoom, V., Boldrin, D., Leung, A. K., Sookkrajang, C., and Likitlersuang, S. (2022). Biomechanical properties of the growing and decaying roots of *Cynodon dactylon*. *Plant Soil* 471, 193–210. doi: 10.1007/s11104-021-05207-1

Kang, E., Li, Y., Zhang, X., Yan, Z., Wu, H., Li, M., et al. (2021). Soil pH and nutrients shape the vertical distribution of microbial communities in an alpine wetland. *Sci. Total Environ.* 774:145780. doi: 10.1016/j.scitotenv.2021.145780

Kumar, S., and Chong, I. (2018). Correlation analysis to identify the effective data in machine learning: prediction of depressive disorder and emotion states. *Int. J. Environ. Res. Public Health* 15:2907. doi: 10.3390/ijerph15122907

Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. *Science* 304, 1623–1627. doi: 10.1126/science.1097396

Lama, G. F. C., Errico, A., Francalanci, S., Chirico, G. B., Solari, L., and Preti, F. (2020a). "Hydraulic modeling of field experiments in a drainage channel under different riparian vegetation scenarios" in *Springer*. eds. A. Coppola, G. Carlo, G. Altieri and P. D'Antonio (Heidelberg, Germany: Springer International Publishing), 67, 69–77.

Lama, G. F. C., Errico, A., Francalanci, S., Solari, L., Preti, F., and Chirico, G. B. (2020b). Evaluation of flow resistance models based on field experiments in a partly vegetated Reclamation Channel. *Geosciences* 10:47. doi: 10.3390/geosciences10020047

Lamarque, L. J., Félix-Faure, J., Deschamps, L., Lévesque, E., Cusson, P.-O., Fortier, D., et al. (2023). Hydrological regime and plant functional traits jointly mediate the influence of Salix spp. on soil organic carbon stocks in a high Arctic tundra. *Ecosystems* 26, 1238–1259. doi: 10.1007/s10021-023-00829-1

Lee, H., Deeb, T. Z., Walker, J. A., Davies, P. A., and Moss, S. J. (2011). NMDA receptor activity downregulates KCC2 resulting in depolarizing GABAA receptor–mediated currents. *Nat. Neurosci.* 14, 736–743. doi: 10.1038/nn.2806

Li, J. J., Li, L. J., Arif, M., Ding, D. D., Hu, X., and Li, C. X. (2023b). Newly formed riparian microhabitats simplify bacterial community structure and diversity. *J. Soils Sediments* 23, 1927–1943. doi: 10.1007/s11368-023-03454-6

Li, J. J., Muhammad, A., Ding, D. D., Hu, X., Gen, Q., Yin, F., et al. (2023a). The diversity of plant communities in different habitats can lead to distinct methanotrophic communities. *Rhizosphere* 26:100690. doi: 10.1016/j.rhisph.2023.100690

Li, C., Wang, X., and Qin, M. (2021). Spatial variability of soil nutrients in seasonal rivers: a case study from the Guo River basin, China. *PLoS ONE* 16:e0248655. doi: 10.1371/journal.pone.0248655

Li, X., Zhu, W., Xu, F., Du, J., Tian, X., Shi, J., et al. (2021). Organic amendments affect soil organic carbon sequestration and fractions in fields with long-term contrasting nitrogen applications. *Agric. Ecosyst. Environ.* 322:107643. doi: 10.1016/j.agee.2021.107643

Licata, M., Farruggia, D., Iacuzzi, N., Leto, C., Tuttolomondo, T., and Miceli, G. D. (2022). Effect of irrigation with treated wastewater on bermudagrass (*Cynodon dactylon* (L.) Pers.) production and soil characteristics and estimation of plant nutritional input. *PLoS One* 17:e0271481. doi: 10.1371/journal.pone.0271481

Liu, Y.-F., Liu, Y., Shi, Z.-H., López-Vicente, M., and Wu, G.-L. (2020). Effectiveness of re-vegetated forest and grassland on soil erosion control in the semi-arid loess plateau. *Catena* 195:104787. doi: 10.1016/j.catena.2020.104787

Liu, L., Zhu, K., Wurzburger, N., and Zhang, J. (2020). Relationships between plant diversity and soil microbial diversity vary across taxonomic groups and spatial scales. *Ecosphere* 11:e02999. doi: 10.1002/ecs2.2999

Long, L., Liu, Y., Chen, X., Guo, J., Li, X., Guo, Y., et al. (2022). Analysis of spatial variability and influencing factors of soil nutrients in Western China: a case study of the Daliuta mining area. *Sustainability* 14:2793. doi: 10.3390/su14052793

Maharajan, T., Ceasar, S. A., Krishna, T. P. A., and Ignacimuthu, S. (2021). Management of phosphorus nutrient amid climate change for sustainable agriculture. *J. Environ. Qual.* 50, 1303–1324. doi: 10.1002/jeq2.20292

Mahohi, A., and Raiesi, F. (2021). The performance of mycorrhizae, rhizobacteria, and earthworms to improve Bermuda grass (*Cynodon dactylon*) growth and Pb uptake in a Pb-contaminated soil. *Environ. Sci. Pollut. Res.* 28, 3019–3034. doi: 10.1007/s11356-020-10636-z

Majumdar, A., and Avishek, K. (2023). Riparian zone assessment and management: an integrated review using geospatial technology. *Water Air Soil Pollut.* 234:319. doi: 10.1007/s11270-023-06329-1

Makoto, K., and Koike, T. (2021). Charcoal ecology: its function as a hub for plant succession and soil nutrient cycling in boreal forests. *Ecol. Res.* 36, 4–12. doi: 10.1111/1440-1703.12179

Matos, P. S., da Silva, C. F., Damian, J. M., Cerri, C. E. P., Pereira, M. G., and Zonta, E. (2021). Beneficial services of Glomalin and arbuscular mycorrhizal fungi in degraded soils in Brazil. *Sci. Agric.* 79:e20210064. doi: 10.1590/1678-992X-2021-0064

Meng, C., Liu, H., Wang, Y., Shen, J., Liu, F., Xia, Y., et al. (2023). Landscape pattern exhibits threshold-driven effect on nitrogen export of typical land use in subtropical hilly watershed under specific hydrological regimes. *J. Clean. Prod.* 419:138322. doi: 10.1016/j.jclepro.2023.138322

Mokgakane, T. J., Mlambo, V., Ravhuhali, K. E., and Magoro, N. (2021). Contribution of soil type to quantity and nutritional value of grass species on the south African Highveld. *Resources* 10:106. doi: 10.3390/resources10100106

Moore, L., Evans, K., Lau, H., Riley, L., Erickson, V., and Taylor-Davenport, R. (2023). "Roadside restoration with native plants: partnering for success in the Pacific northwest of the USA" in *Ecological restoration: Moving forward using lessons learned*. eds. S. Florentine, P. Gibson-Roy, K. W. Dixon and L. Broadhurst (Berlin, Germany: Springer International Publishing), 325–368.

Msimbira, L. A., and Smith, D. L. (2020). The roles of plant growth promoting microbes in enhancing plant tolerance to acidity and alkalinity stresses. *Front. Sustain. Food Syst.* 4:106. doi: 10.3389/fsufs.2020.00106

Muscetta, M., Bianco, F., Trancone, G., Race, M., Siciliano, A., D'Agostino, F., et al. (2023). Washing bottom sediment for the removal of arsenic from contaminated Italian coast. *PRO* 11:902. doi: 10.3390/pr11030902

Nakamura, F. (2022). *Green infrastructure and climate change adaptation: Function, Implementation and Governance*. Berlin, Germany: Springer Nature.

Narayanan, M., and Ma, Y. (2023). Mitigation of heavy metal stress in the soil through optimized interaction between plants and microbes. *J. Environ. Manag.* 345:118732. doi: 10.1016/j.jenvman.2023.118732

Ni, J. J., Bordoloi, S., Shao, W., Garg, A., Xu, G., and Sarmah, A. K. (2020). Two-year evaluation of hydraulic properties of biochar-amended vegetated soil for application in landfill cover system. *Sci. Total Environ.* 712:136486. doi: 10.1016/j.scitotenv.2019.136486

Ni, Y., Yang, T., Ma, Y., Zhang, K., Soltis, P. S., Soltis, D. E., et al. (2021). Soil pH determines bacterial distribution and assembly processes in natural mountain forests of eastern China. *Glob. Ecol. Biogeogr.* 30, 2164–2177. doi: 10.1111/geb.13373

Nisa, R. U., Tantray, A. Y., Kouser, N., Allie, K. A., Wani, S. M., Alamri, S. A., et al. (2021). Influence of ecological and edaphic factors on biodiversity of soil nematodes. *Saudi J. Biol. Sci.* 28, 3049–3059. doi: 10.1016/j.sjbs.2021.02.046

Nsenga Kumwimba, M., Huang, J., Dzakpasu, M., De Silva, K., Ohore, O. E., Ajibade, F. O., et al. (2023). An updated review of the efficacy of buffer zones in warm/temperate and cold climates: insights into processes and drivers of nutrient retention. *J. Environ. Manag.* 336:117646. doi: 10.1016/j.jenvman.2023.117646

Odoh, C. K., Sam, K., Zabbey, N., Eze, C. N., Nwankwegu, A. S., Laku, C., et al. (2020). "Microbial consortium as biofertilizers for crops growing under the extreme habitats" in *Plant microbiomes for sustainable agriculture*. eds. A. N. Yadav, J. Singh, A. A. Rastegari and N. Yadav (Berlin, Germany: Springer International Publishing), 381–424.

Olagoke, O. V., Babaniyi, G. G., Afolabi, F. J., and Babaniyi, B. R. (2022). "Soil microbial enzymes and mitigation of heavy metal uptake by plants" in *Ecological interplays in microbial enzymology*. eds. N. R. Maddela, A. S. Abiodun and R. Prasad (Berlin, Germany: Springer Nature), 215–246.

Omoarelojie, L. O., and van Staden, J. (2023). Perspectives on the potentials of phlorotannins in enhancing phytoremediation performance. *J. Plant Growth Regul.* 42, 1–21. doi: 10.1007/s00344-023-11075-z

Opitz, J., Alte, M., Bauer, M., and Peiffer, S. (2021). The role of Macrophytes in constructed surface-flow wetlands for mine water treatment: a review. *Mine Water Environ.* 40, 587–605. doi: 10.1007/s10230-021-00779-x

Padulano, R., Lama, C., Rianna, G., Santini, M., Mancini, M., and Stojiljkovic, M. (2020). Future rainfall scenarios for the assessment of water availability in Italy. *IEEE International Workshop on Metrology for Agriculture and Forestry (Metro Agri For)* 2020, 241–246. doi: 10.1109/MetroAgriFor50201.2020.9277599

Penn, C. J., and Camberato, J. J. (2019). A critical review on soil chemical processes that control how soil pH affects phosphorus availability to plants. *Agriculture* 9:120. doi: 10.3390/agriculture9060120

Piccoli, I., Seehusen, T., Bussell, J., Vizitu, O., Calciu, I., Berti, A., et al. (2022). Opportunities for mitigating soil compaction in Europe—case studies from the soil care project using soil-improving cropping systems. *Land* 11:223. doi: 10.3390/land11020223

Pirone, D., Cimorelli, L., Del Giudice, G., and Pianese, D. (2022). Short-term rainfall forecasting using cumulative precipitation fields from station data: a probabilistic machine learning approach. *J. Hydrol.* 617:128949. doi: 10.1016/j.jhydrol.2022.128949

Prasad, S., Malav, L. C., Choudhary, J., Kannojiya, S., Kundu, M., Kumar, S., et al. (2021). "Soil microbiomes for healthy nutrient recycling" in *Current trends in microbial biotechnology for sustainable agriculture*. eds. A. N. Yadav, J. Singh, C. Singh and N. Yadav (Berlin, Germany: Springer), 1–21.

Proto, M., and Courtney, R. (2023). Application of organic wastes to subsoil materials can provide sustained soil quality in engineered soil covers for mine tailings rehabilitation: a 7 years study. *Ecol. Eng.* 192:106971. doi: 10.1016/j.ecoleng.2023.106971

Rafique, M., Ortas, I., Ahmed, I. A. M., Rizwan, M., Afridi, M. S., Sultan, T., et al. (2019). Potential impact of biochar types and microbial inoculants on growth of onion plant in differently textured and phosphorus limited soils. *J. Environ. Manag.* 247, 672–680. doi: 10.1016/j.jenvman.2019.06.123

Rangel-Peraza, J., Padilla-Gasca, E., Lopez Corrales, R., Rochín Medina, J., Bustos-Terrones, Y. A., Amabilis-Sosa, L., et al. (2017). Robust soil quality index for tropical soils influenced by agricultural activities. *J. Agricult. Chem. Environ.* 6, 199–221. doi: 10.4236/jacen.2017.64014

Rathod, D. M. K., Sugunavathi, K., Annapurna, D., and Kumari, B. K. (2023). *A textbook on basics of environmental science*. Oxford, United Kingdom: Routledge.

Rauf, Z., Zarif, N., Khan, A., Siddiqui, S., Fatima, S., Iqbal, W., et al. (2023). The Western Himalayan fir tree ring record of soil moisture in Pakistan since 1855. *Int. J. Biometeorol.* 67, 1477–1492. doi: 10.1007/s00484-023-02517-0

Ray, R., Das, A., Hasan, M. S. U., Aldrees, A., Islam, S., Khan, M. A., et al. (2023). Quantitative analysis of land use and land cover dynamics using Geoinformatics techniques: a case study on Kolkata metropolitan development authority (KMDA) in West Bengal, India. *Remote Sens.* 15:959. doi: 10.3390/rs15040959

Rendana, M., Idris, W., Abd Rahim, S., Ali Rahman, Z., Lihan, T., and Jamil, H. (2018). Reclamation of acid sulphate soils in paddy cultivation area with organic amendments. *AIMS Agricult. Food* 3, 358–371. doi: 10.3934/agrfood.2018.3.358

Said, M. K., and Misana, S. B. (2022). Effects of land cover changes and forest fragmentation on three species of east African mini-antelopes. *Afr. J. Ecol.* 62:e13170. doi: 10.1111/aje.13170

Shahbaz, M., Rashid, N., Saleem, J., Mackey, H., McKay, G., and Al-Ansari, T. (2023). A review of waste management approaches to maximise sustainable value of waste from the oil and gas industry and potential for the State of Qatar. *Fuel* 332:126220. doi: 10.1016/j.fuel.2022.126220

Shen, M., Song, B., Zhou, C., Almatrafi, E., Hu, T., Zeng, G., et al. (2022). Recent advances in impacts of microplastics on nitrogen cycling in the environment: a review. *Sci. Total Environ.* 815:152740. doi: 10.1016/j.scitotenv.2021.152740

Singh, P., Sharma, S., and Dhanorkar, M. (2022). Aquatic plant biomass-derived porous carbon: biomaterials for sustainable waste management and climate change mitigation. *Int. J. Environ. Sci. Technol.* 20, 12955–12970. doi: 10.1007/s13762-022-04601-1

Siqueira, P. P., Oliveira, P. T. S., Bressiani, D., Meira Neto, A. A., and Rodrigues, D. B. B. (2021). Effects of climate and land cover changes on water availability in a Brazilian Cerrado basin. *J. Hydrol. Reg. Stud.* 37:100931. doi: 10.1016/j.ejrh.2021.100931

Stumpf, L., Fernandez, M. B. D. G., Miguel, P., Pinto, L. F. S., Schubert, R. N., Filho, L. C. O., et al. (2022). "Impact of revegetation on ecological restoration of a constructed soil in a coal Mining in Southern Brazil" in *Vegetation dynamics, changing ecosystems and human responsibility* (London, United Kingdom: Intech Open)

Tan, S., Narayanan, M., Thu Huong, D. T., Ito, N., Unpaprom, Y., Pugazhendhi, A., et al. (2022). A perspective on the interaction between biochar and soil microbes: a way to regain soil eminence. *Environ. Res.* 214:113832. doi: 10.1016/j.envres.2022.113832

Tu, A., Xie, S., Zheng, H., Li, H., Li, Y., and Mo, M. (2021). Long-term effects of living grass mulching on soil and water conservation and fruit yield of citrus orchard in South China. *Agric. Water Manag.* 252:106897. doi: 10.1016/j.agwat.2021.106897

Tuozzo, S., Ciccaglione, M. C., Buccino, M., Ascione, G., and Calabrese, M. (2022). Wave overtopping at a vertical seawall by boussinesq modeling. The 32nd International Ocean and polar engineering conference, all days, ISOPE-I-22-430.

Voltr, V., Menšík, L., Hlisnikovský, L., Hruška, M., Pokorný, E., and Pospíšilová, L. (2021). The soil organic matter in connection with soil properties and soil inputs. *Agronomy* 11:Article 4. doi: 10.3390/agronomy11040779

Wang, J., and Delavar, M. A. (2023). Techno-economic analysis of phytoremediation: a strategic rethinking. *Sci. Total Environ.* 902:165949. doi: 10.1016/j.scitotenv.2023.165949

Wang, C., Zhou, X., Guo, D., Zhao, J., Yan, L., Feng, G., et al. (2019). Soil pH is the primary factor driving the distribution and function of microorganisms in farmland soils in northeastern China. *Ann. Microbiol.* 69, 1461–1473. doi: 10.1007/s13213-019-01529-9

Wu, G.-L., Liu, Y.-F., Cui, Z., Liu, Y., Shi, Z.-H., Yin, R., et al. (2020). Trade-off between vegetation type, soil erosion control and surface water in global semi-arid regions: a meta-analysis. *J. Appl. Ecol.* 57, 875–885. doi: 10.1111/1365-2664.13597

Wu, D., Wang, X., and Yin, P. (2023). Allelopathic effects of *Salix matsudana* (Koidz) root exudates on soil bacterial diversity. Available at: https://web.s.ebscohost.com/abstract?direc.

Yan, S., Zhang, S., Xu, B., Yan, P., Wang, J., Wang, H., et al. (2023). Microplastics change the leaching of nitrogen and potassium in Mollisols. *Sci. Total Environ.* 878:163121. doi: 10.1016/j.scitotenv.2023.163121

Yang, Q., Bejarano, M. D., Ma, W., Salam, M., Pu, B., Wei, H., et al. (2023). Effects of long-term submergence on non-structural carbohydrates and N and P concentrations of *Salix matsudana* along the three gorges reservoir. *Hydrobiologia* 850, 2035–2047. doi: 10.1007/s10750-023-05215-5

Ye, F., Hong, Y., Wu, J., Yi, X., Op den Camp, H. J. M., Moore, S. S., et al. (2022). Succession of soil microbial community in a developing mid-channel bar: the role of environmental disturbance and plant community. *Front. Microbiol.* 13:970529. doi: 10.3389/fmicb.2022.970529

Yusof, N. N. M., Khairiyah, S., Hatta, M., Kamarudin, S. H., Suratman, M. N., Supardan, S. N., et al. (2023). "Land degradation and restoration: Implication and management perspective," in *Land and environmental management through forestry*. (Beverly, Massachusetts, USA: Scrivener Publishing LLC), 1–21.

Zanli, B. L. G. L., Gbossou, K. C., Tang, W., Kamoto, M., and Chen, J. (2022). A review of biochar potential in cote d'Ivoire in light of the challenges facing sub-Saharan Africa. *Biomass Bioenergy* 165:106581. doi: 10.1016/j.biombioe.2022.106581

Zhang, G., Bai, J., Tebbe, C. C., Zhao, Q., Jia, J., Wang, W., et al. (2021). Salinity controls soil microbial community structure and function in coastal estuarine wetlands. *Environ. Microbiol.* 23, 1020–1037. doi: 10.1111/1462-2920.15281

Zheng, J., Arif, M., He, X., Liu, X., and Li, C. (2023). Distinguishing the mechanisms driving multifaceted plant diversity in subtropical reservoir riparian zones. *Front. Plant Sci.* 14:1138368. doi: 10.3389/fpls.2023.1138368

Zhong, Z., Zhang, X., Wang, X., Fu, S., Wu, S., Lu, X., et al. (2020). Soil bacteria and fungi respond differently to plant diversity and plant family composition during the secondary succession of abandoned farmland on the loess plateau, China. *Plant Soil* 448, 183–200. doi: 10.1007/s11104-019-04415-0

Zhu, X., Liu, W., Chen, J., Bruijnzeel, L. A., Mao, Z., Yang, X., et al. (2020). Reductions in water, soil and nutrient losses and pesticide pollution in agroforestry practices: a review of evidence and processes. *Plant Soil* 453, 45–86. doi: 10.1007/s11104-019-04377-3