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Differences in dissolved organic matter and analysis of influencing factors between plantations pure and mixed forest soils in the loess plateau

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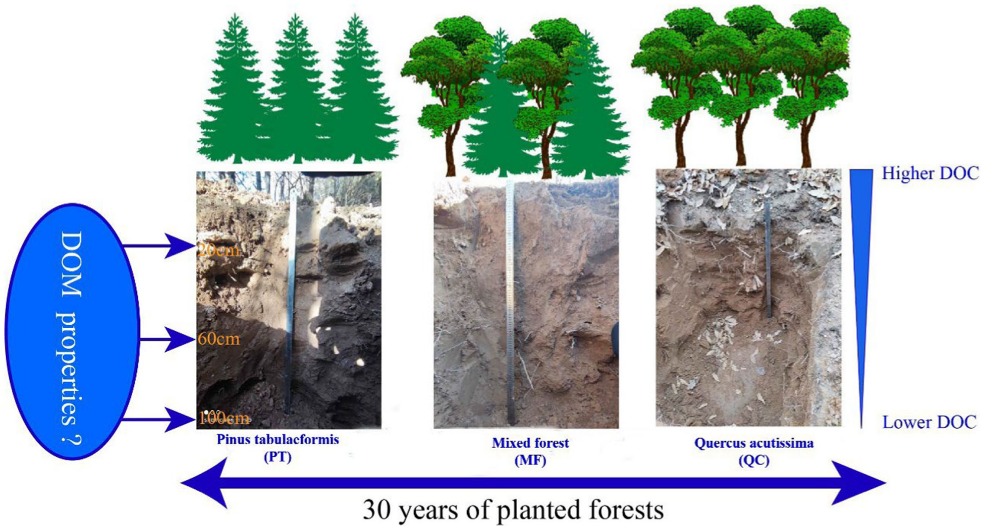
The dissolved organic matter (DOM) in forest ecosystems significantly impacts soil carbon cycling due to its active turnover characteristics. However, whether different plantation forest soil profiles exhibit distinct DOM characteristics remains unclear. Hence, utilizing fluorescence spectroscopy and the parallel factor analysis (PARAFAC) method, a 1-meter soil profile analysis was carried out on three distinct artificial forests (*Pinus tabuliformis* (PT), Quercus crispula (QC), and a mixed forest of PT and QC (MF)), concurrently assessing the impact of soil chemical properties and enzyme activity on dissolved organic matter (DOM). The findings indicated that the mean concentration of dissolved organic carbon (DOC) was greatest in the MF and lowest in PT, exhibiting considerable variation with soil depth, suggesting that mixed tree species may promote the discharge of organic matter. The fluorescence spectra revealed two distinct peaks: humic-like fluorescence peaks (Peaks A and C) and a protein-like fluorescence peak (Peak T), with the most intense fluorescence observed in MF soil. As the soil depth increased, the fluorescence intensity of Peaks A and C steadily declined, while the intensity of Peak T rose. Four DOM components were identified in three types of plantations forests: surface soil was dominated by humic acid-like fluorescent components (C1 and C2), while the deep soil was primarily characterized by protein-like fluorescence components (C3 and C4). Different soil profile fluorescence parameter indices indicated that the source of DOM in the surface soil (i.e., 0–20 cm) was mainly allochthonous inputs, whereas, in the deep soil (i.e., 60–100 cm), it was mainly autochthonous, such as microbial activity. The findings from the partial least squares path modeling (PLS-PM) revealed that TP, aP, NH_4^+-N, and the combined impact of soil enzymes were influential in shaping the diversity of DOM attributes. Put differently, alterations in DOM concentration were concomitantly influenced by forest classification, soil characteristics, and depth. It has been demonstrated that, in contrast to monoculture forests, the establishment of mixed forest models has been more advantageous in enhancing the soil dissolved organic matter (DOM). These discoveries offer innovative perspectives on the dynamic characteristics of DOM in soil profiles and its influencing factors under different plantations forest planting patterns.

KEYWORDS

loess plateau, coniferous and broadleaved mixed forest, dissolved organic matter, soil profile, parallel factor analysis



GRAPHICAL ABSTRACT

Highlights

- The dissolved organic carbon (DOC) content in order was MF (*Quercus acutissima* mixed forest) > QC (*Quercus acutissima*) > PT (*Pinus tabulaeformis*).
- Surface soil DOM was mainly humic acid substances, while deep soil DOM was mainly tryptophan substances.
- Mixed forest species were more beneficial for increasing soil organic matter than single species forests.

1 Introduction

Forest-derived dissolved organic matter (DOM) has various chemical compositions and heterogeneous physical properties (Smith et al., 2013; Xu and Guo, 2017). DOM participates a significant in the cyclical changes of carbon of forest ecosystems and facilitates the migration, transformation, cycling of organic matter in the entire ecological environment (Bolan et al., 2011; Batjes, 2014). In forest ecosystems, DOM originates from the decay and degradation of organic matter, substances produced by animal and microbial metabolism, secretions from plant roots, and litter produced during plant growth (Jaffrain et al., 2010; Kaiser and Kalbitz, 2012). Owing to the unique hydrological pathways of forest ecosystems, rainwater percolates through penetrates the surface litter layer, inevitably exerting a strong influence on the further downward migration of DOM (Thieme et al., 2019). Additionally, different forest stand types are important factors influencing the origin of DOM. For example, DOM in coniferous forests primarily originates from the decomposition of plant biomass, such as leaves, bark, and branches, whereas DOM in broadleaf forests is mainly derived from leaf litter decomposition and root exudates (Kiikkilä et al., 2006). Therefore, it is vital to characterize the DOM components of different forest species and the vertical depth of soil to understand the carbon cycling processes in this region.

Decaying debris, root systems, and microbial secretions in forests are potential nutrient sources for soil microbes, promoting microbial proliferation, and thus releasing DOM into the soil (Schmidt et al., 2011). Different soil minerals have varying abilities and selectivity for the adsorption of DOM, which ultimately affects the stability and decomposition rate of organic matter (Saidy et al., 2013; Liu et al., 2023a). However, different vegetation types have significantly different effects on soil enzymes. Research by He et al. (2020) indicated that, compared to coniferous tree species, broadleaf tree species had higher levels of C-cycle-related enzymes (β-glucosidase, BG). Guo et al. (2023) emphasized through meta-analysis that the mixture of tree species had a positive impact on the soil nutrients and enzyme activity of fir trees. The physicochemical properties of the soil, metabolic processes of soil microorganisms, and catalytic effects of soil enzymes are key driving factors in the differentiation of DOM profiles in the soil (Hu et al., 2021; Li H. et al., 2022). The availability of soil microbiota and enzymes is usually influenced by soil depth (Goberna et al., 2005; Eilers et al., 2012; Stone et al., 2014), possibly due to oxygen limitation and soil properties (Ko et al., 2017). A recent study used parallel factor analysis (PARAFAC) and found that soil physicochemical properties are important factors affecting DOM, whereas microbial metabolism and enzyme activity were identified as factors that further influenced DOM at a deeper level (Li W. et al., 2022). Thieme et al. (2019) observed that the composition of DOM varies based on the tree species, while investigating coniferous, deciduous, and unmanaged birch forests. Li W. et al. (2022) identified that the dominant component of DOM in the surface soil of Larix principis-rupprechtii in North China was humic substances, which originated from plant residues. Although these results indicate that the migration of dissolved organic matter (DOM) in soil profiles is influenced by plant inputs, microbial processing, and re-synthesis, limited studies have only focused on the DOM characteristics in soils of single tree species. The effects brought

Abbreviations: DOM, Dissolved organic matter; DOC, Dissolved organic carbon; TN, Total nitrogen; TP, Total phosphorus; $NH4^+$-N, Ammonia nitrogen; aP, available phosphorus; NAG, β-1,4-N-acetyglucosaminidase; LAP, L-Leucine aminopeptidase; BG, β-glucosidase; EG, Cellulase; EC, β-xylosidase; AP, Alkaline phosphatase.

about by mixed forest planting patterns are increasingly evident, such as improving forest structure and increasing species diversity. However, it remains unclear whether this pattern affects DOM. Moreover, data on different DOM characteristics in soil profiles of artificial forests, which are important forest resources, are still limited.

The Loess Plateau, an important ecological security barrier in China, is one of the world's most ecologically fragile areas. To improve land productivity and safeguard the living environment of the people, the government has implemented large-scale afforestation policies and conducted extensive reforestation efforts (Wang et al., 2013; Meng et al., 2022). Studying the characteristics of DOM in the soils of plantation forests in this region provides insights into the impact of plantation forests on soil properties and carbon cycling. Common plantations tree species in here include *Pinus tabuliformis* (PT, coniferous) and *Quercus acutissima Carruth* (QC, broad-leaved), both of which have significantly different effects on soil. Coniferous tree leaves are difficult to decompose, resulting in soil acidification (Jílková et al., 2019). Compared with needle leaves, broad leaves are more easily decomposed, resulting in the enrichment of soil organic matter (SOM) and an increase in soil fertility (Song et al., 2016). However, mixed forests of coniferous and broad-leaved trees typically have high SOM accumulation and low organic matter decomposition rates, leading to carbon sequestration (Li et al., 2022). Consequently, exploring the characteristics of DOM in plantation forests is crucial for a deeper understanding of the properties of plantation forest soils and their impact on carbon cycling, especially in the Loess Plateau region.

The aims of this study are to (1) investigate the vertical distribution characteristics of soil DOM spectra in different forest stands, and (2) explore the response of soil DOM to the interaction between soil physicochemical properties and soil enzymes. This study provides novel insights into the changes and potential driving factors of soil DOM under different planting modes and helps to facilitate future studies on soil fertility and carbon storage in plantation forests.

2 Materials and methods

2.1 Study description

The soil samples were collected the northern part of the Shuanglong State-owned Ecological Experimental Forest Farm, Huangling County, Yan'an City, China. The geographical coordinates are 108°45′32″ E—109°1′21″ E and 35°33′7″ N—35°49′30″ N. This region has a warm-temperate continental monsoon climate. The soil is classified as grey-brown, with less noticeable soil calcification and silicification, which creates favourable conditions for tree growth. The predominant tree species include *Pinus tabulaeformis*, *Chamaecyparis fortunei*, *Larix gmelinii*, *Quercus* spp., *Betula platyphylla*, *Robinia pseudoacacia*, *Populus davidiana*, and deciduous and evergreen hardwoods. The trees in the plantation are approximately 30 years. The locations of the watersheds under study are depicted in Figure 1, while Table 1 provides essential information about the study plots.

2.2 Soil sampling

In March 2023, sampling was conducted in three representative plantation forests within the study area, with a distance of ≥50 m between each site. These forests included *Pinus tabuliformis* forest (PT), *Quercus acutissima Carruth* forest (QC), and mixed forests of *Pinus tabuliformis* and *Quercus acutissima* Carruth (MF). In each type of plantations forest, profile sampling was conducted at a depth of 1 m, divided into three depth levels: 0–20 cm, 20–60 cm, and 60–100 cm. This process was repeated three times for each treatment group. To prevent cross-contamination, 27 samples were divided into two groups and placed in sterile bags. One group of soil samples was stored at 4°C after handling (air-drying at room temperature and passing through a 2 mm and 0.15 mm sieve). The other group was stored in a −20°C refrigerator to determine soil enzyme activities.

2.3 Laboratory analyses

The filtrate was analysed using a Vario TOC Cube Select Total Organic Carbon Analyser (Elementar, Germany). Total phosphorus (TP), available phosphorus (aP), and ammonia nitrogen (NH_4^+-N) were analysed using an automated discontinuous chemical analyser (Clever Chem 200, Germany). Total N (TN) was analysed using a FOSS automatic Kjeldahl nitrogen analyser (Kjeltec 8400, United States). All specific measurement methods for the chemical properties are described in Supplementary Text S1.

According to Sinsabaugh et al. (2010) and Parham and Deng (2000), six soil enzymes involved in C, N, and P cycling were selected (Table 2). Soil enzyme activity was measured using a 96-well microplate assay, as described by Saiya-Cork et al. (2002) and Xiao et al. (2023). 1.0 g of fresh soil was suspended in a buffered solution and shaken for 1 h to create a suspension. An aliquot of the suspension and corresponding fluorescent substrates specific to the soil enzymes were added to the microplate. Fluorescent substrates and buffers were added as blanks, with six replicates for each sample. The microplate was incubated containing soil enzymes at 25°C for a specified period of time (Xiao et al., 2020).

The dissolved organic carbon (DOC) solution was obtained by mixing soil with deionized water at a ratio of 1:5 w/v (Jones and Willett, 2006). After oscillation and centrifugation, it was filtered through a 0.45 μm organic membrane to obtain the DOC filtrate for measurement. The DOC filtrate was diluted with ultrapure water to obtain a DOM solution, to ensure that the concentration of soluble organic matter was within the desired range (using an absorbance of 0.10 at 254 nm as a reference point) and reducing the fluorescence quenching effect. An Aqualog fluorescence spectrophotometre (Horiba, Tokyo, Japan) was used. The excitation and emission wavelength ranges were from 230 to 600 nm, with a 3 nm interval and a 1-s integration time of 1 s. The Aqualog system automatically corrected for filter and Rayleigh scattering to provide corrected data.

2.4 Spectral parameters and PARAFAC modeling

To further investigate the spectral and source characteristics of DOM, we calculated various fluorescence spectral parameters (Table 3 and Supplementary Text S2). To address the issue of overlapping spectra and to quantitatively analyze the composition of DOM, the PARAFAC method was used to analyze the fluorescence spectroscopy data (Supplementary Text S3). The reliability of the results was verified

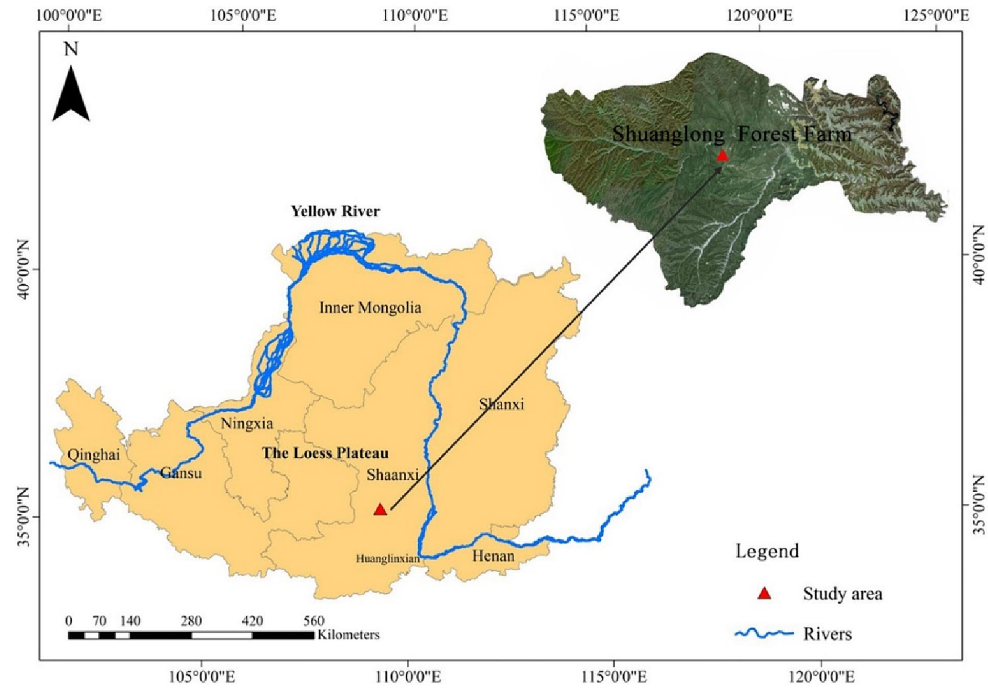


FIGURE 1
Schematic illustration of soil sampling locations in plantations forests on the Loess Plateau.

using a nuclear consistency function and half-analysis (Stedmon and Bro, 2008).

2.5 Data analysis and statistics

We assessed significant differences in parameters across sampling points parameters using two-way ANOVA in SPSS Statistics software (version 21.0). Pearson correlation analysis was performed in R 4.0.3 to evaluate the correlation between the parameters. Origin 2021 (Northampton, Massachusetts, OriginLab Inc.) was used to analyse and plot the changes in soil chemical properties, soil enzyme activity, and spectral data. PLS-PM was used to predict the impact of soil enzymes and chemical properties on DOM.

3 Results

3.1 Soil properties and DOM content

The depth of the soil and the type of vegetation had a significant impact on the soil chemical properties (Figure 2). The chemical properties of the soil (TN, NH_4^+-N, TP, and aP) varied significantly at different depths. For different soil profiles within the same vegetation type, the soil chemical properties (TN, NH_4^+-N, and TP) decreased as the soil depth increased across all three types. Among different soil types within the same profile, the TN values were highest in MF (0.71–2.30 mg/kg), followed by QC (0.63–1.71 mg/kg) and PT (0.57–1.38 mg/kg). The sequence of NH_4^+-N variations was QC < MF < PT, with NH_4^+-N values ranging from 6.82 to 10.11 mg/kg in QC, 6.57 to 9.37 mg/kg in MF, and 4.95 to 8.36 mg/kg in PT. The average TP values in PT and QC soils were significantly higher than in MF. In the surface layer (0–20 cm), the TP concentration in QC was significantly higher than in the other two forests (PT and MF), at 221.92 mg/kg. The aP values of the three forest types fluctuated across different profiles, with the highest average concentration of aP in the 0–20 cm layer of MF soil (51.81 mg/kg). The concentration of aP decreased in the 20–60 cm layer but increased in the 60–100 cm layer. The trend of aP concentration variations in the PT profile was consistent with that of MF.

TABLE 1 Basic characteristics of the sample plots.

Stand type	Stand age	Area/ hm^2	Mean DBH/ cm	Mean height/ cm	Canopy density
QD	27	18.72	12.6	14.1	0.62
PC	32	12.26	16.4	13.6	0.6
MF	30	20.84	13.6	15.2	0.7

The DOC content of the three vegetation types decreased with increasing soil depth (Table 4). The average DOC content was highest in MF and QC forests, exceeding that of PT (16.18–24.25 mg/L). Additionally, the variations in the a(355) values along the soil profile were consistent with the changes in DOC concentration. However, for different soil types within the same profile, the decreasing order of DOC content at 0–20 cm and 20–60 cm was: QC < PT < MF. This indicates that the biological characteristics of different forest types result in significant differences in soil DOC content.

TABLE 2 Six types of soil enzyme types and their abbreviation (He et al., 2021).

Enzyme	Model	Substrate	Abbreviation
β-1,4-N-acetyglucosaminidase	37067-30-4	4-MUB-β-D-cellobioside	NAG
L-Leucine aminopeptidase	62480-44-8	L-Leucine-7-amino-4-methylcoumarin	LAP
β-glucosidase	18997-57-4	4-MUB-β-D-glucoside	BG
Cellulase	72626-61-0	4-Methylumbelliferone-β-D-Fibrodiglycoside	EG
β-xylosidase	6734-33-4	4-Methylumbelliferyl-β-D-xyloside	EC
Alkaline phosphatase	3368-04-5	4-MUB-phosphate disodium salt	AP

TABLE 3 Spectral parameters description.

Parameters	Formula	Meaning and description of formula parameters
Fluorescence index (*FI*)	The ratio of fluorescence intensity between $Ex = 370$ nm and $Em = 450$ nm to $Em = 500$ nm.	$FI < 1.4$ indicates allochthonous inputs, while $FI > 1.9$ indicates autochthonous sources dominate (Gabor et al., 2014; Zhang et al., 2017).
Humification index (*HIX*)	The ratio of the average fluorescence intensity between $Ex = 254$ nm and $Em = 435$-480 nm to that between 300-345 nm.	$HIX > 16$ indicates strong humification character with obvious terrigenous inputs; $6 < HIX < 10$ represents strong humification character and weak autochthonous character; $4 < HIX < 6$ indicates moderate humification character; $HIX < 4$ indicates autochthonous sources dominate (Ohno, 2002).
Autogenic index (*BIX*)	The ratio of fluorescence intensity between $Ex = 310$ nm and $Em = 380$ nm to $Em = 430$ nm.	$BIX > 1$ means biological or bacterial origin; $0.8 < BIX < 1$ means strong autochthonous features; $0.7 < BIX < 0.8$indicates moderate recent autochthonous features; $0.6 < BIX < 0.7$ implies a relatively large allochthonous inputs (Gao et al., 2017).
$a(355)$	$a(355) = 2.303 \times D(355)/L$	where $D(355)$ stands for absorbance at (355) nm wavelength, and L stands for optical path length, L is the optical path (Zhang et al., 2009).
$SUVA_{254}$	$SUVA_{254} = a(355)/DOC$	A higher SUV_{254} value indicates a higher content of aromatic compounds in DOM, indicating a higher level of aromaticity (Dilling and Kaiser, 2002).

3.2 Changes in soil enzyme activity concentration

As shown in Figure 3, the activities of three soil enzymes related to carbon cycling (BG, EC, and EG) and soil microbial secretion of enzymes for nitrogen and phosphorus acquisition (NAG, LAP, and AP) all sharply decreased with depth. Additionally, there were significant differences in soil enzyme activities among the depths of the three vegetation types. In the surface layer (0–20 cm) and (20–60 cm) of soil, except for EC and LAP enzymes, the soil enzyme activities in the MF forest were at least twice as high as those in the QC and PT forests, following a decreasing pattern of PT < QC < MF. In the 60–100 cm soil depth, the enzyme activity in the QC forest was the highest, which may be related to the litter production, decomposition rate, and root biomass of different forest types.

3.3 Spectroscopic properties of DOM

The fluorescence spectral characteristics of DOM at different soil depths in the three forest types were identified. The samples had two fluorescence peaks, namely a humus type fluorescence peak (peak A and peak C), and a protein-like fluorescence peak (peak T), as shown in Supplementary Figure S1. In the soils of the three forest types, the fluorescence intensity revealed a consistent pattern with all fluorescence peaks following the same pattern: MF > PT > QC (Figure 4). Simultaneously, with the increase in soil depth, the fluorescence intensity of A peak and C peak gradually decreased, while the intensity of T peak increased. This is related to the properties of the litter, compared with broad-leaved litter, coniferous litter contains significant amounts of cellulose and lignin, which are difficult to decompose, cellulose and lignin, these substances decompose slowly, accumulating recalcitrant materials that can polymerize into humus in the soil.

The PARAFAC model resolved four components of samples (Figure 5). C1 is a humic substance, represented by humic acids (Yamashita et al., 2010). C2 is a high molecular weight aromatic amino acid and is a fulvic-like acid components (Stedmon et al., 2003). C3 is a typical protein-like fluorescent component associated with microbial activity. C4 is a component of tryptophan-like substances (Zhang et al., 2022). C1 and C2 are fluorescent components that could reflect the quality of SOM, whereas C3 and C4 was a type of fluorescent components related to protein in soil, and is generally associated with microbial protein metabolites (Stedmon et al., 2003; He et al., 2014). In the surface soil (0–20 cm), only C1 and C2 were present, while in the deeper soil, C3 and C4 components were also present. It is worth noting that the proportion of C3 and C4 increased with increasing soil depth.

3.4 Changes in DOM fluorescence parameters

To further distinguish and compare the sources and properties of the DOM components, we calculated fluorescence parameter indicators for different soil profiles separately, as shown in Figure 6. The FI values of the three forest types showed that below a depth of 60 cm, were below 1.4, indicating that the input from soil

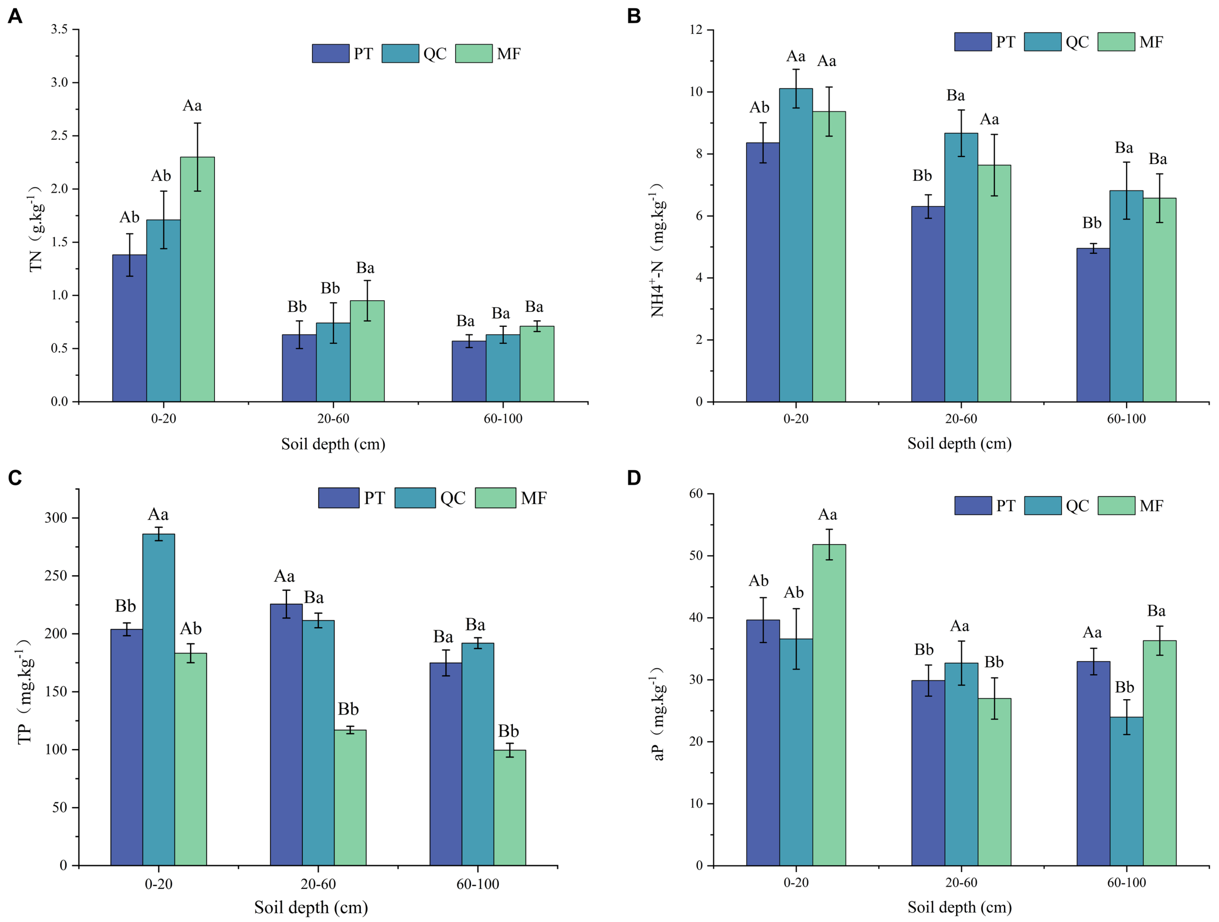


FIGURE 2
Characteristics of chemical properties of three forest types of soil vertical sections. **(A)** Total nitrogen(TN). **(B)** Ammonia nitrogen ($NH4^+$-N). **(C)** Total phosphorus (TP). **(D)** Available phosphorus (aP). Capital letters denote marked enzyme activity differences in profiles of the same tree species; lowercase indicates significant variations among species within a profile (p < 0.05).

TABLE 4 Soil DOC and a (355) content of three forest types in different soil layers (mg/L).

Depth (cm)	Index	PT	QC	MF
0–20	DOC	22.07 ± 4.14Ab	38.25 ± 8.61Aa	46.32 ± 9.22Aa
20–60		9.47 ± 2.65Bb	10.48 ± 2.35Ba	11.15 ± 3.15Ba
60–100		5.42 ± 1.36Bb	6.19 ± 1.87Ba	6.36 ± 0.88Ba
0–20	a(355)	22.66 ± 5.74Aa	13.27 ± 3.64Ab	23.07 ± 2.84Aa
20–60		6.989 ± 2.20Ba	4.71 ± 0.17Bb	8.23 ± 1.42Ba
60–100		4.64 ± 3.91Bb	6.72 ± 2.45Ba	7.02 ± 1.58Ba

Uppercase letters indicate significant differences in DOC and a(355) between different profiles of the same tree species; lowercase letters indicate significant variations in DOC and a(355) within the same profile of tree species (p<0.05).

leaching was the main factor. In the soil profile of the 60–100 cm layer, the FI value ranged from 1.4 to 1.9, indicating that the DOM in the soil was influenced by both allochthonous and autochthonous inputs. The HIX and BIX indicators exhibited opposite trends along the soil profile. The HIX continued to decrease as the soil depth increased, whereas the BIX showed the opposite trend. This indicates that at a depth of 0–20 cm, the DOM had strong humification and weak endogenous characteristics. However, as the soil depth increased, DOM showed strong autochthonous characteristics. $SUVA_{254}$ values indicated a significant decrease in DOM aromaticity in deep soil layers, with a consistent pattern observed across the three soil types. In addition, the $SUVA_{254}$ value of PT was greater, suggesting a greater degree of humification in the PT. Overall, in the three soil types, the source of DOM in the source of DOM in the surface soil (0–20 cm) was mainly allochthonous, whereas in deep soil (60–100 cm) originating mainly from endogenous sources, such as microbial activity.

3.5 Correlation index analysis and PLS-PM

DOC exhibited significant positive correlations (p < 0.01) with TN, aP and a(355), as well as with the four enzymes LAP, NAG, BG, and AP (Figure 7A). However, TN was negatively correlated with TP, and the soil enzyme indicators showed no significant correlation with TP. Building upon the results of the correlation analysis, a PLS-SEM model was adopted to investigate the effects of soil depth, chemical properties, and enzymes on DOM. The arrows in Figure 7B indicate the direction of influence of one variable on another, and the adjacent numbers indicate the standardised path coefficients. DOM received a positive

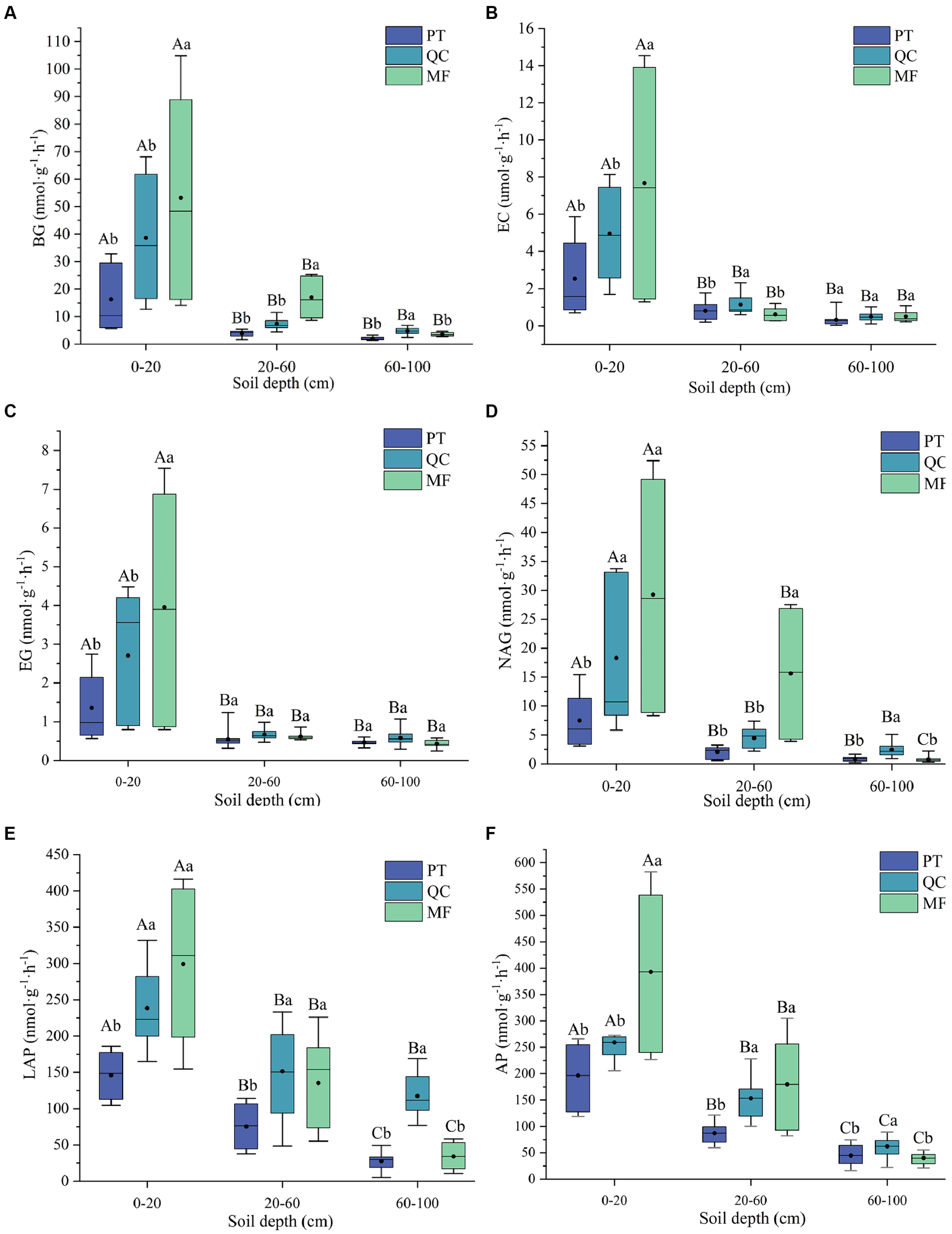


FIGURE 3
Vertical variation characteristics of soil enzyme activity in three forest types. **(A)** Activities of β-glucosidase (BG). **(B)** Activities of β-xylosidase (EC). **(C)** Activities of Cellulase (EG). **(D)** Activities of β-1,4-N-acetyglucosaminidase (NAG). **(E)** Activities of L-Leucine aminopeptidase (LAP). **(F)** Activities of Alkaline phosphatase (AP). Capital letters denote marked differences in enzyme activity between profiles of the same tree species, while lowercase indicates significant differences among tree species within a profile ($p < 0.05$).

contribution from soil enzymes in all models; however, while chemical properties had a positive impact on DOM, this impact did not reach a significant level. Soil depth had a negative direct path coefficient for both the chemical properties and soil enzymes. The effect of soil chemical properties on DOM was mainly achieved indirectly through various soil enzymes related to the soil C, N, and P cycles.

4 Discussion

4.1 Differences in DOM storage among three forest types

DOC directly or indirectly influences the biogeochemical cycling in forest soil. Its component dynamics and turnover are mainly controlled

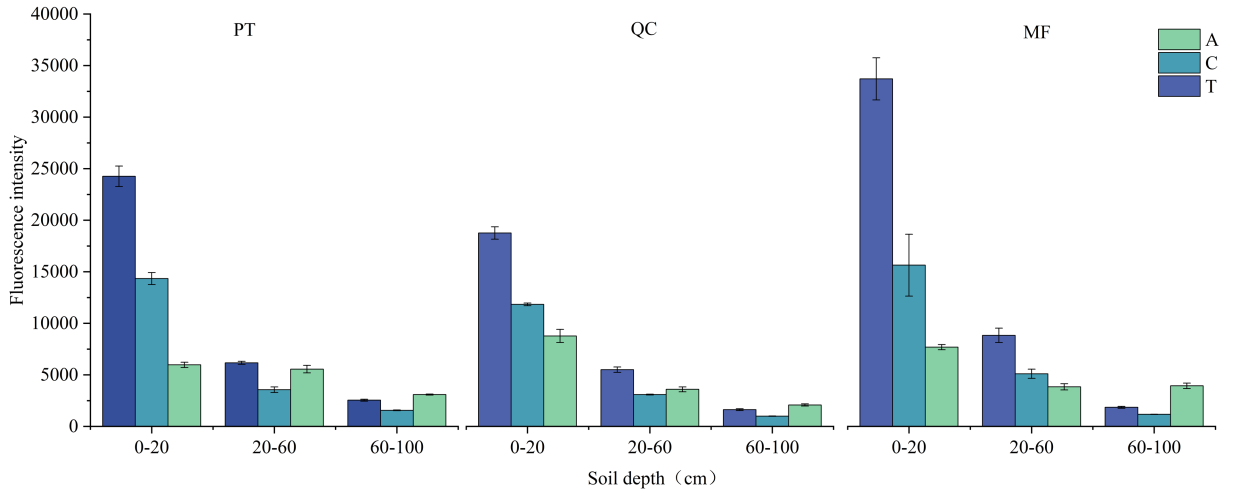


FIGURE 4
Changes in fluorescence spectral intensity with profile.

by changes in the forest vegetation type, litter input type, soil temperature, and humidity (Gruba and Socha, 2019). DOC, an important component of DOM, is typically used to characterize the concentration of DOM (Zhang et al., 2017). The DOC values of the soil at depths of 0–20 cm (22.07–46.32 mg/L) and 20–60 cm (9.47–11.15 mg/L) in the area were comparable to the values of subtropical forest tree species (0–20 cm:37.10–47.40 mg/L; 20–60 cm:4.80–9.50 mg/L) (Tu et al., 2011). DOC distribution and changes in soil profiles have certain regularities (McDowell and Likens, 1988; Gabor et al., 2014; McDowell, 2022), and the content of DOC in the surface soil layer is usually greater than that in the bottom soil layer. The elevated levels of DOC in the upper layers of forest soil mainly arise from the leachates of the canopy and litter; however, the decrease in DOC levels may be related to losses caused by adsorption and decomposition during downward migration in soil minerals, leading to a decrease in DOC levels with increasing depth (Tu et al., 2011). Therefore, the three types of forest soils exhibited consistent patterns in vertical depth. This aligns with the research findings regarding dissolved organic carbon (DOC) in the coniferous, broad-leaved, and mixed conifer-broadleaf forests of Shennongjia Forest and Dinghu Mountain Forest (Gu et al., 2023). Furthermore, the surface-level concentrations of DOC were notably elevated in MF and QC compared to PT, due in part to the greater levels of litter products, root exudates, and microbial biomass in the MF and QC forests (Weintraub et al., 2007), leading to the generation of more DOC.

4.2 Fluorescent component characteristics of DOM

Proteins in soil organic matter can provide nutrition and energy to microorganisms, which can promote the maintenance and improvement of soil fertility (McFarland et al., 2010). In fact, biochemical processes driven by microorganisms can easily break down the proteins used by microorganisms into monomeric molecules, which can then be polymerised to form humus through aggregation processes (Yan et al., 2019). We found that the fluorescence peak value of the humus type gradually decreased with increasing soil depth, whereas the protein fluorescence peak exhibited the opposite trend. This result indicates that the decayed branches and leaves in the forest were preserved on the soil surface, hence, the humus content was higher. The aromatic substances produced by trees can chemically react with soil and are stably preserved in soil (Wei et al., 2020). The fluorescence peaks A and C, formed by the input of exogenous humic-acid and fulvic acid, have stable structures (Ussiri and Johnson, 2003). Furthermore, the PARAFAC model showed that in surface soil (0–20 cm), only humic components C1 and C2 existed. This is mainly because of the long-term accumulation of forest litter, which provides a material basis for microbial growth, effectively promotes the accumulation of C1 and C2 substances in the soil. C3 and C4 accumulate in deep soil, indicating a gradual increase in microbial products. A possible explanation for this phenomenon could be that the surface soil DOM was easily influenced by the vegetation type (Kaiser and Kalbitz, 2012). As the soil depth increased, DOM was retained through adsorption and precipitation. The microbial community could consume and decompose key components of DOM while involving the generation of new molecules, leading to changes in DOM composition. Therefore, the dominant components of deep soil were C3 and C4 plants (Roth et al., 2019). This is similar to previous findings on the characteristics of DOM of different tree species in plantations forests (Ye et al., 2020). In addition, the three indicators FI, HIX, and BIX showed that with increasing soil depth (Figure 5), the self-generated sources caused by microbial activity became more significant. The $SUVA_{254}$ values displayed that the aromaticity of DOM decreased with soil depth, and the molecular weight of the DOM was accompanied by low-quality aromatics. In temperate grassland soils, the same phenomenon has also been recorded (Roth et al., 2019), indicating that fresh plant-derived organic matter is rapidly degraded and low-quality polyphenols are rapidly consumed. Therefore, in the vertical migration of soil layers, DOM was a process of continuous decomposition, adsorption, and transformation, closely related to soil properties and microbial activity.

4.3 The interaction between physicochemical properties and soil enzymes is essential for understanding soil DOM

Different vegetation types produce different qualities of litter and root exudates, resulting in differences in soil chemical properties (Weiss

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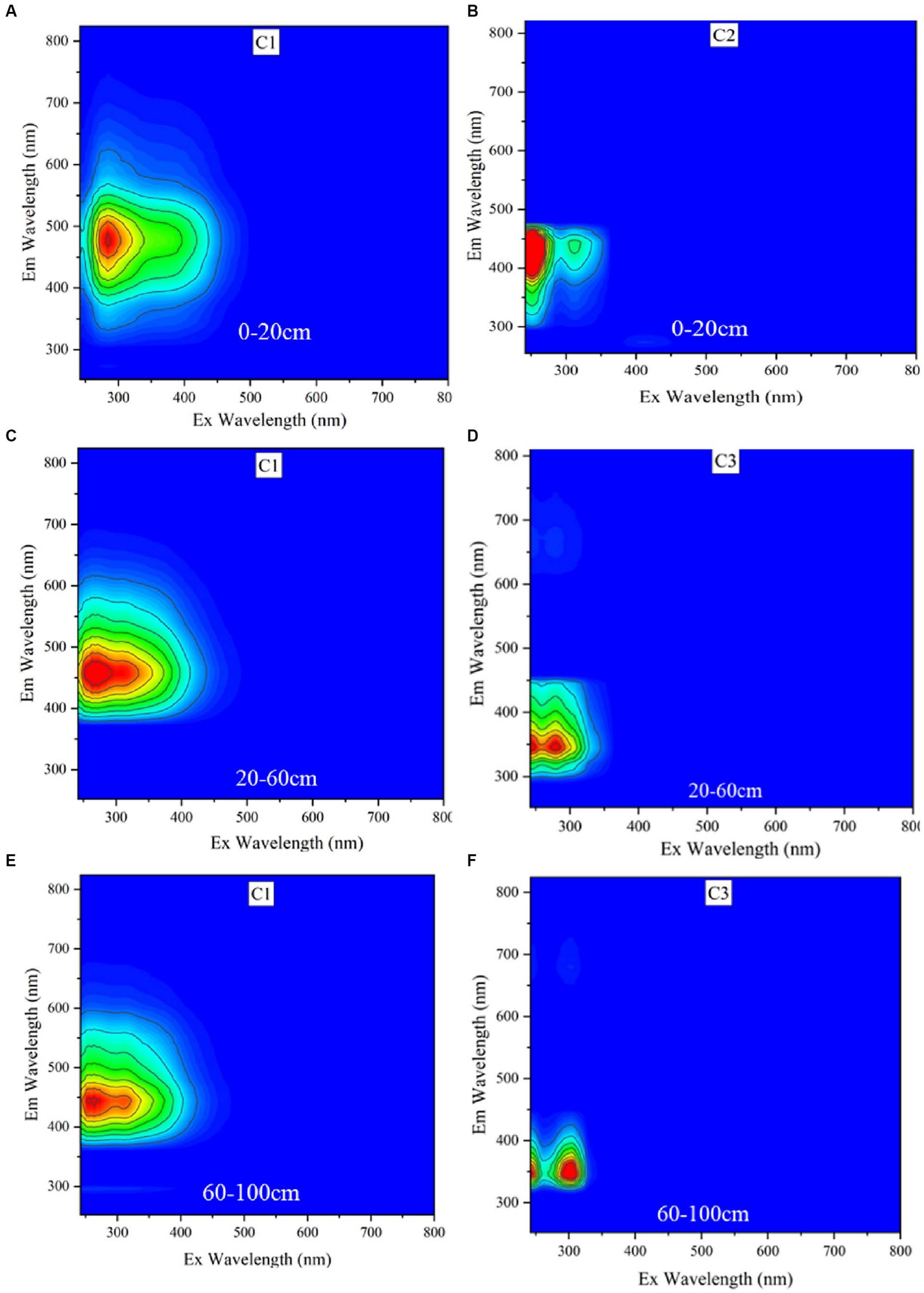

FIGURE 5 (Continued)

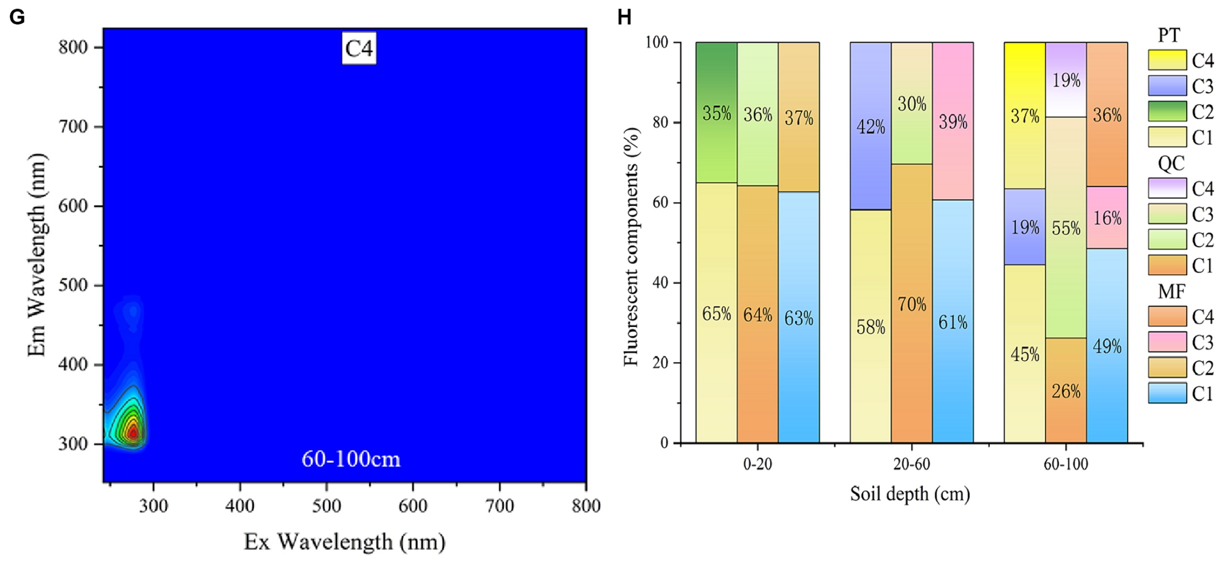

FIGURE 5
DOM fluorescence component diagram. Ex, excitation wavelength; Em, emission.

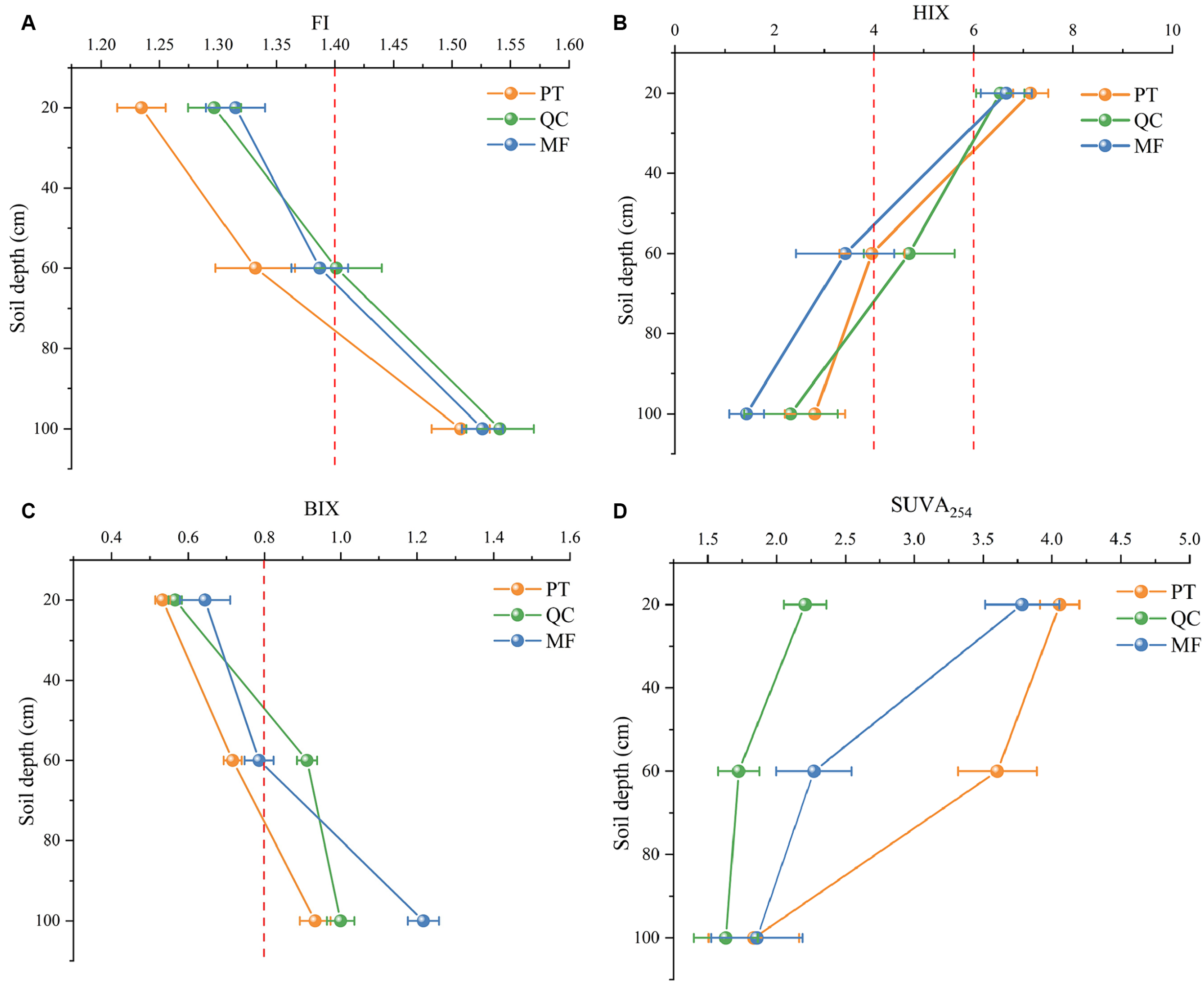

FIGURE 6
Optical indices of soil DOM of the three plantations forest types (PL, QC, and MF) at depths of 20, 60, and 100 cm. **(A)** Fluorescence Index (*FI*). **(B)** Humification index (*HIX*). **(C)** Autogenic index (*BIX*). **(D)** Parameters indicating the level of aromaticity ($SUVA_{254}$).

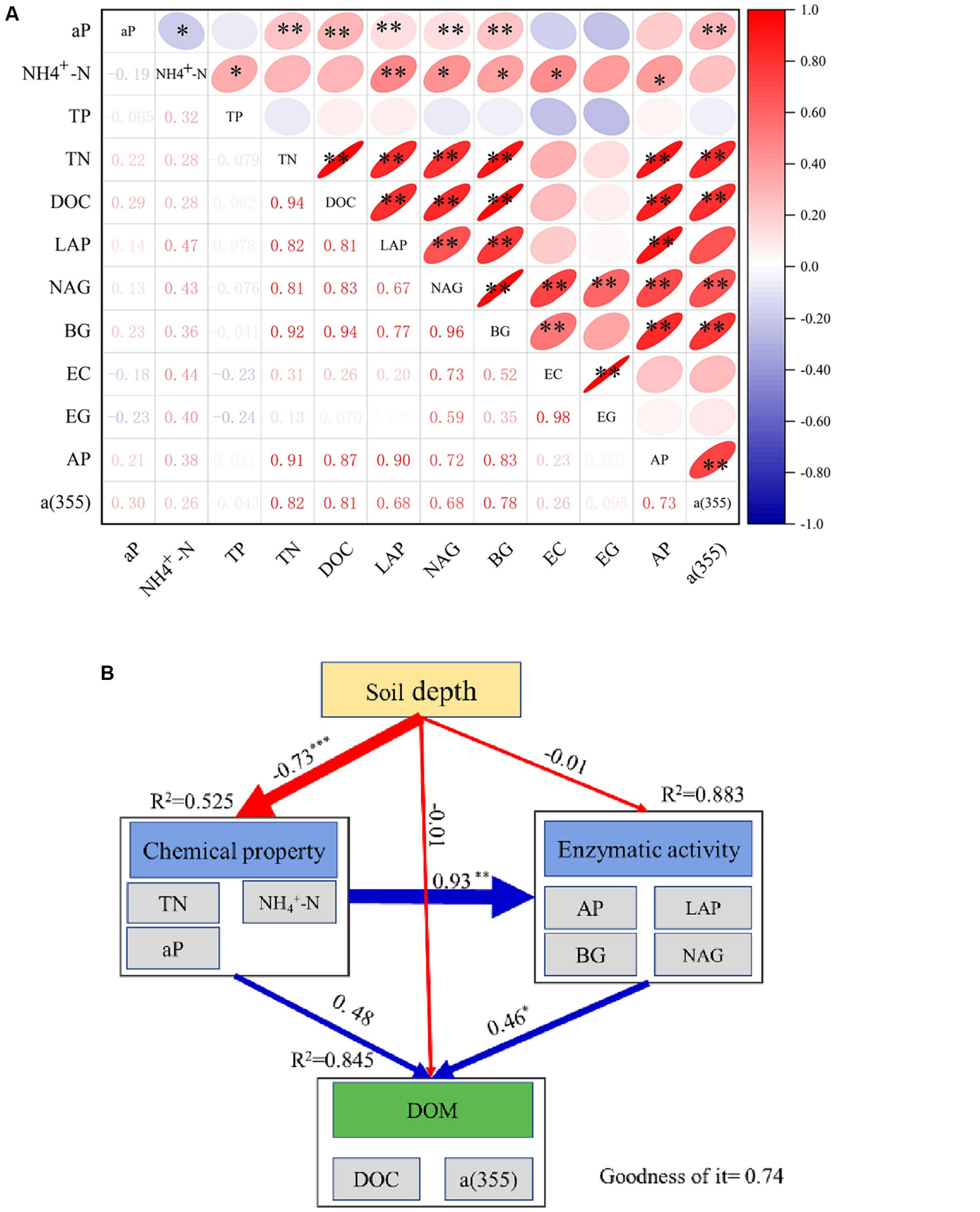

FIGURE 7
Correlation analysis and PLS-PM models. **(A)** Correlations among the reflecting indicators; $**p < 0.01$, $*p < 0.05$. **(B)** Results of the PLS-PM models for DOM. The reflecting indicators of the chemical property were a:NH_4^+-N, TN, TP and aP. The reflecting indicators of the enzymatic activity were AP, LAP, BG, NAG; $*p < 0.05$, $**p < 0.01$, $***p < 0.005$.

et al., 2016; Liu et al., 2023b), and these physical and chemical properties can indirectly affect soil enzyme activity by influencing the composition and species of soil microorganisms. Since each enzyme has a specific substrate and the ability to catalyze biochemical reactions, it inevitably affects Soil Organic Carbon (SOC) pools (Chandra et al., 2016). During our research, DOM in forest soils was closely correlated with soil enzyme activity. The enzymes associated with C, N, and P cycling were found to have a highly significant correlation with DOC (Figure 7). PLS-PM analysis showed that soil chemical properties mainly influenced DOM through the activity of various enzymes. Owing to differences in litter input, enzyme activity, and soil microbes among the different forest types, the concentration of DOM varies. Soil enzyme activity was limited by vegetation type, which exerts a considerable influence on enzyme activity in the soil. Consistent with findings from other studies on forested areas, mixed forests were able to promote an increase in soil enzyme activity (Zhang et al., 2008; He et al., 2020). This suggests that mixed tree species stimulate soil enzyme activity, which may be attributed to three potential mechanisms. First, mixed forests alleviate soil acidification by decomposing alkaline cations in fallen leaves and branches (Hong et al., 2018); second, mixed forests have a lower bulk density, thereby improving soil aeration (Qian et al., 2022); third, higher physicochemical properties increase soil enzyme activity, which in turn promotes the release of organic matter (Singh et al., 2012). Therefore, mixed-species plantations forests are more effective at accumulating soil organic matter. In addition, a single forest type causes biodiversity loss, seriously affecting the carbon sequestration function of the soil (Lu et al., 2018; Islam et al., 2022). In contrast, mixed-species forests have a positive effect on ecosystem carbon storage (Hulvey et al., 2013; Gong et al., 2022). In conclusion, mixed-species forests are more beneficial for increasing soil organic matter compared to monoculture forests. In afforestation practices, increasing the number of mixed species can most effectively improve soil environmental quality and enhance soil ecological functions, without considering economic limitations.

5 Conclusion

The study revealed that the DOC content followed the sequence of MF > QC > PT, with a significant decrease observed in the deeper soil layers. This may be due to varying litter production and root exudate levels among the forest types. The vertical distribution pattern of soil enzyme activity was consistent with the DOC pattern, indicating that mixed species could stimulate soil enzyme activity, leading to an increase in soil enzyme activity and subsequently promoting the release of organic matter. Additionally, the dominant components in the surface soil were C1 and C2, while in the deep soil, C3 and C4 were predominant. This suggests that the vertical migration of DOM in the soil profile is a continuous process of decomposition and adsorption of new substances. Furthermore, the three indices (FI, HIX, and BIX) indicated that the influence of microbially induced local sources on the lower layer DOM became more prominent. PLS-PM analysis revealed that the impact of soil chemical properties on DOM was mainly mediated through various soil enzymes. In conclusion, mixed tree species are more conducive to improving soil organic matter compared to single tree species. Future research should continue to emphasize the interactions among soil chemical properties, soil enzymes, and DOM under different artificial forest planting patterns.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

YM: Writing – review & editing, Writing – original draft, Software, Investigation, Formal analysis, Conceptualization. PL: Writing – review & editing, Methodology. LX: Writing – review & editing. BH: Writing – original draft, Software. CZ: Writing – review & editing, Data curation. SY: Writing – original draft, Software. JL: Writing – original draft, Software. BZ: Writing – review & editing, Data curation.

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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

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/ffgc.2024.1344784/full#supplementary-material

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