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Impact of Fertilizers Application on Leaf Litter Decomposition and Nutrient Cycling in White Poplar (*Populus alba L.*) Forest Ecosystem

Monira Fayaz[a], Abdul Baess Keyhani[b], Danish Bakhshyar[a,c], Li Zhaoguo[a], Md. Zahirul Islam[a] and Guang Yang[a]

[a]Key Laboratory of Sustainable Forest Ecosystem Management of Ministry of Education College of Forestry, Northeast Forestry University, Harbin, 150040, China; [b]College of Horticulture and Forestry Sciences, Huazhong Agricultural University, Wuhan, 430070, China; [c]Faculty of Chemical Engineering, Kunming University of Science and Technology, Kunming, 65000, China

ABSTRACT

Fertilizer application plays a crucial role in the decomposition of white poplar leaf litter and cycling of nutrients within forest ecosystems. The impact of various fertilizer additions on white poplar leaf litter and nutrient cycling is poorly understood. In this study, seven treatments were conducted at the following levels: Control (CK), no adding mineral fertilizers, N fertilization (+N), N and P fertilization (+NP), N, P, K fertilization (+NPK), P, K (+PK), manure fertilizer (+MF), and bird fertilizers (+BF) in a white poplar plantation in Qadis district, and used the litterbag techniques to measure litter mass remaining. The main objectives of our study were: (1) to explore the response of white poplar leaf litter decomposition to various fertilizers and accelerate the decomposition process; (2) to examine the relationship between C, N, and P concentration and their stoichiometric characteristic in leaf litter and soil. In this investigation, our results showed that white poplar leaf litter was significantly affected by fertilizers, and the decomposition process was greatly accelerated with +MF, +NPK, and +BF. The decay rate constant k (year $^{-1}$) shows the decomposition rate of white poplar leaf litter as follows: +MF > +NPK > +BF > +PK > +NP > +N > CK (0.56, 0.53, 0.52, 0.51, 0.51, 0.5, and 0.46). Soil nutrients N, P and K increased significantly during the decomposition time with +MF, +NPK, and +BF, respectively, while C:N, C:P, and N:P ratios were highest in the white poplar leaf litter, and lowest in soil, we observed significant association between nutrients concentrations in soil and white poplar leaf and their stoichiometric. This current study concluded that adding +MF, +NPK and +BF fertilizers might be the preferred management option as they provided potentially beneficial changes in leaf litter decomposition and increased nutrient concentration. The data obtained will be a valuable reference for fertilization management strategies in forest ecosystems.

1. Introduction

Leaf litter decomposition is a critical ecological process that supports nutrient cycling, soil health, carbon sequestration, and ecosystems overall functioning and sustainability (Li et al., 2023; Su et al., 2023; Wu et al., 2023) and is an essential process that regulates the cycling of nutrients and carbon in most terrestrial ecosystems (Allen et al., 2020; Cai et al., 2021; Liu et al., 2022). Accelerating leaf decomposition with fertilizers promotes rapid nutrient cycling in the ecosystem, and leaf litter contains valuable nutrients. Accelerating the decomposition of leaf litter releases nutrients into the soil and helps maintain soil fertility, which is important for the overall health and productivity of the forest (Hu et al., 2021; Song et al., 2020). The rate of decomposition and patterns of nutrient release depends on abiotic factors such as climate conditions and soil physical and chemical properties and biotic factors like litter quality and microbial community composition (Fanin et al., 2020; Liu et al., 2023; Shao et al., 2023; Teague and Dowhower, 2022). At the global scale, the decomposition of plant leaf litter is mostly influenced by both climate and litter quality (Akoto et al., 2022; Ouyang et al., 2022; Pang et al., 2022; Swart et al., 2022); on a local scale, it is influenced by the chemical properties of the leaf litter and the soil conditions of the site (Ren et al., 2018; Song et al., 2016; Xie et al., 2016).

Several studies in different ecosystems have been conducted to explore the effects of fertilizers on leaf litter decomposition (Su et al., 2021; Zhang et al., 2020; Zhu et al., 2016). However, the reactions of leaf litter decomposition to fertilizer addition have varied significantly,

ranging from positive outcomes (Gurung et al., 2023; Wachendorf et al., 2020; Wu et al., 2023) to neutral (Dong et al., 2020; Khalsa et al., 2020; Nakatsuka et al., 2020) to negative (Cornwell et al., 2008; Micks et al., 2004; Zhou et al., 2017). Several chemical, biological, and biochemical hypotheses have been suggested to elucidate the potential mechanisms behind the diverse impact of N deposition on litter decomposition. Despite these efforts, our understanding of the effects of different fertilizers on leaf litter decomposition remains limited (Carreiro et al., 2000; Knorr et al., 2005; Liu et al., 2010; Sinsabaugh, 2010).

In the Qadis district, white poplar is one of the highly-valued species and fast-growing species capable of reaching an age of 35-40 years (Brilli et al., 2014). It is distributed widely with broad adaptability, provides a large volume of timber with many applications, and has significant ecological and economic value. In white poplar plantations, management of soil fertility through fertilizer application is needed to inhibit stand retrogression and sustain plantation productivity, but the effect of various fertilizers addition on the leaf litter of white poplar during the decomposition practice has not been evaluated.

In plantations with fast-growing tree species, leaf litter plays an important role in the nutrient cycle, providing a high proportion of mineral nutrients to the soil (González et al., 2020). Soil fertility and nutrient cycling is one of the main concerns for sustainable development (Gruhn et al., 2000). It is estimated that for common deciduous trees, in mature plantations, about 88% of N, 83% of P, and 78% of K are restored through leaf echoes (Das and Chaturvedi, 2005). However, other authors have reported a low reduction rate of 20-40%, suggesting that this ratio is largely dependent on genotype (Salehi et al., 2013). Meiresonne et al. (2007) suggested that, in general, nutrient cycling in poplar stands is efficient with no significant nutrient loss, and that the circulars through the leaf circulars are generally rich in basic cations (Stark et al., 2015). White poplar communities, usually grown in full sun, tolerate wet and nutrient-poor sites (Griu and Lunguleasa, 2016), which are often considered quite sensitive to environmental changes such as nutrient deposition and flooding (Zhang et al., 2016). There have been limited reports regarding the influence of fertilizer application on leaf litter decomposition in the white poplar ecosystem. The insufficient investigation of this topic significantly restricts the precise evaluation of soil C sequestration during elevated nutrient deposition, resulting in an inadequate comprehension of nutrient cycling within the white poplar ecosystem. To address these knowledge gaps, we evaluate the effect of various fertilizer additions on white poplar leaf litter during the decomposition of leaf litter in the white poplar plantation; we collected leaf litter and soil samples from fertilizers treatments at four sampling times in white poplar plantation to determine mass remaining and nutrients concentration through the decomposition procedure. The purpose of our study was (1) to explore the response of white poplar leaf litter to various fertilizers and accelerate the

decomposition process and (2) to examine the association between C, N, P and K concentration and between their stoichiometric characters under different fertilization treatments. We aimed to assess the following hypotheses: (1) fertilizers may accelerate the decomposition process; (2) carbon, nitrogen, phosphorus and potassium concentration may have a great relationship with their stoichiometric under fertilizers treatments.

2. Materials and methods

2.1. Study area and experimental setup

This research was conducted in a white poplar plantation with 6-years stand age in the Qadis district (34° 43′ 26.4″ N, 63° 33′ 12.4″ E), which is located in the southern part of Badghis province, Afghanistan (Figure 1), which has an arid continental climate characterized by cold winters, relatively wet winters (including a peak in spring) and hot summers, with an average annual rainfall around 300 mm, and with an average annual temperature of 24 °C.

In this experiment, leaf litter that had fallen at the beginning of autumn 2021 was collected from the white poplar plantation; after air drying for 14 days at room temperature, 10 g leaf litter samples were employed in nylon mesh zip bags (200×200 mm with 1mm mesh) (Figure 2). We established seven treatments with three replicate plots (5×5 m) at the following levels: Control (CK), with no addition of mineral fertilizers; N fertilization (+N) treatment received 150 kg ha^{-1} y^{-1} of urea (CO (NH$_2$)$_2$); N and P fertilization (+NP) treatment received 150 kg ha^{-1} y^{-1} of urea (CO (NH$_2$)$_2$), and phosphorus pentoxide (P$_2$O$_5$); N, P, K fertilization (+NPK) treatment received 150 kg ha^{-1} y^{-1} of urea (CO (NH$_2$)$_2$), phosphorus pentoxide (P$_2$O$_5$), and potassium oxide (K$_2$O); P, K (+PK) treatment received 150 kg ha^{-1} y^{-1} of phosphorus pentoxide (P$_2$O$_5$), and potassium oxide (K$_2$O); manure fertilizer (+MF) treatment received 150 kg ha^{-1} y^{-1} of manure, and bird fertilizer (+BF) treatment received 150 kg ha^{-1} y^{-1} chicken manure. The fertilizer concentrations used were 46% urea, 46% triple superphosphate, and 50% potassium sulfate, respectively, and the synthetic fertilizer was applied in the summer of 2021. The single litter bags with small pores were then arbitrarily placed on each plot in all litter bags, 252 bags in total (7 treatments × 3 plots × 3 replicates × 4 sampling times). In autumn, winter 2021, spring and summer 2022, leaf litter bags and soil samples were collected from each treatment. At each sampling time three leaf litter bags were randomly removed from each treatment. After removing the roots and residues of other plants from the samples, the samples were dried to a constant mass in an oven at 65 °C for 48 h. The dry mass data was recorded and then the litter was crushed according to the requirements for measuring its chemical properties. Soil samples were collected under the decomposition bag, specifically, from the 5-10 cm depth, and transported to the laboratory. In the laboratory soil samples air dried, all soil samples
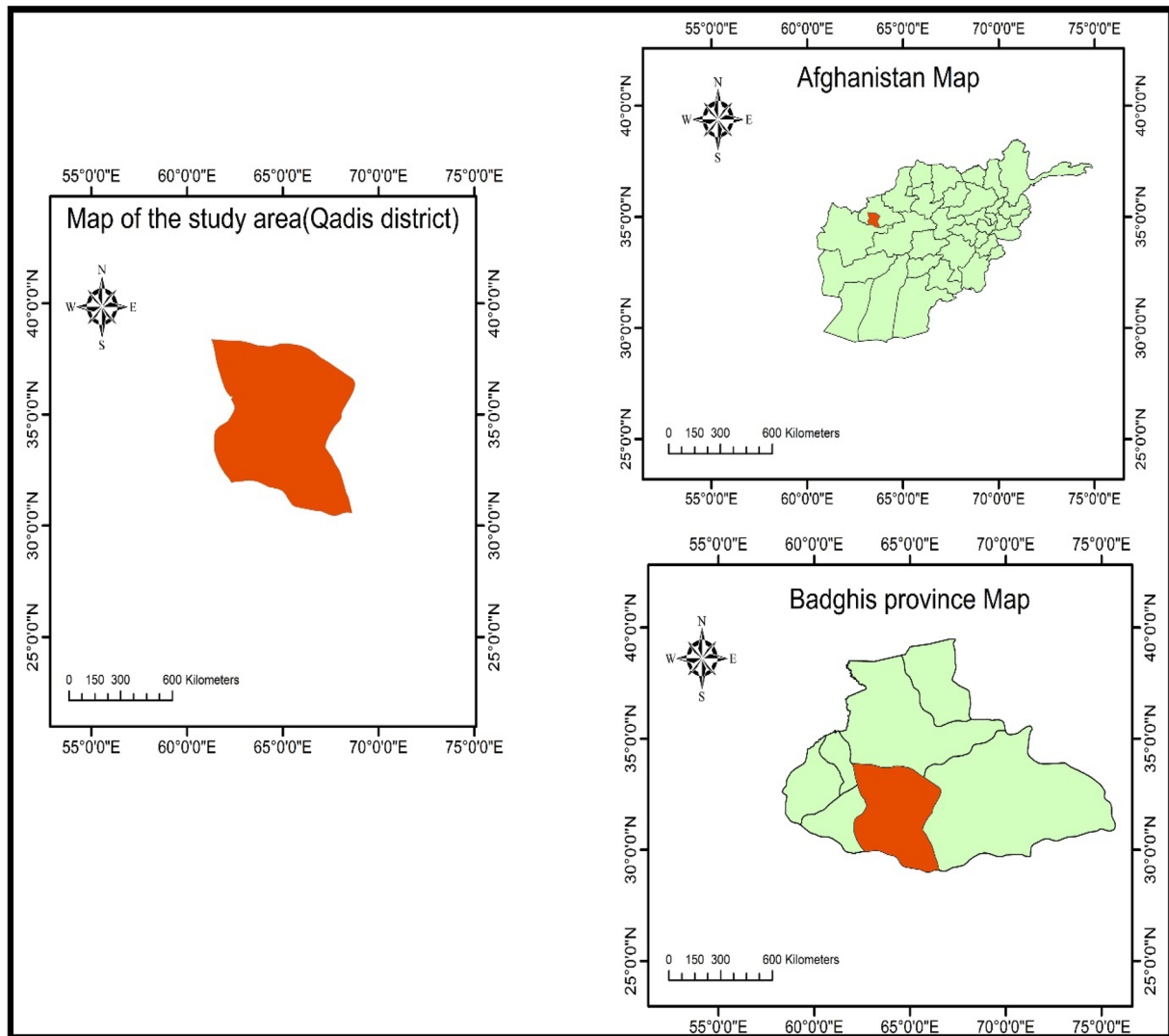
Figure 1. Map of the study area showing the location of Qadis district, in Badghis province, Afghanistan.

were crushed and sieved (2 mm) to eliminate debris and stone material before analyzing of the soil's chemical properties.

2.2. Determination of soil physical and chemical properties and chemical properties of leaf litter

The physical properties of the soil were determined using samples of the undisturbed soil. Kopeck steel cylinders (VS = 100 cm3) were used to take samples from a depth 5-10 cm. Each cylinder (labeled with a unique number) was weighed empty and uncapped and its mass (GV) was noted before sampling. According to (Cai et al., 2021), undisturbed soil samples were used to calculate soil moisture (%), soil bulk density (g/cm3), capillary porosity (%) and non-capillary porosity (%). The pH value of the soil was measured in water using a glass electrode (Mettler-Toledo, Greifensee, Switzerland) and soil organic carbon (SOC) and carbon in leaf litter were determined by the heating method (potassium dichromate digestion: ($K_2Cr_2O_7$). Total nitrogen (TN) and total phosphorus (TP) in soil and leaf litter were determined using an AUTCHEM 1200 (Changchun Xingrui, China) analyzer and total soil, and leaf litter K

were determined using a flame emission method (Xiang Yi, Hunan, China)

2.3. Data analysis

A single negative exponential decay model was employed to calculate the decomposition rates of leaf litter ($y/y0 = e^{-kt}$). One-way analysis of variance (ANOVA) was used to compare the difference between mean chemical properties of soil and leaf litter values as implemented with the (IBM SPSS Statistics for Windows, Version 22. IBM Corp, Armonk, NY, USA), the spearmen correlation function in Origin Pro 2022 was used to examine the possible association between nutrients concentration in leaf litter, soil, and their stoichiometric.

3. Results

3.1. Response of leaf litter decomposition rate to fertilizer applications

At the end of this investigation, there was a significant difference between control plots and the other
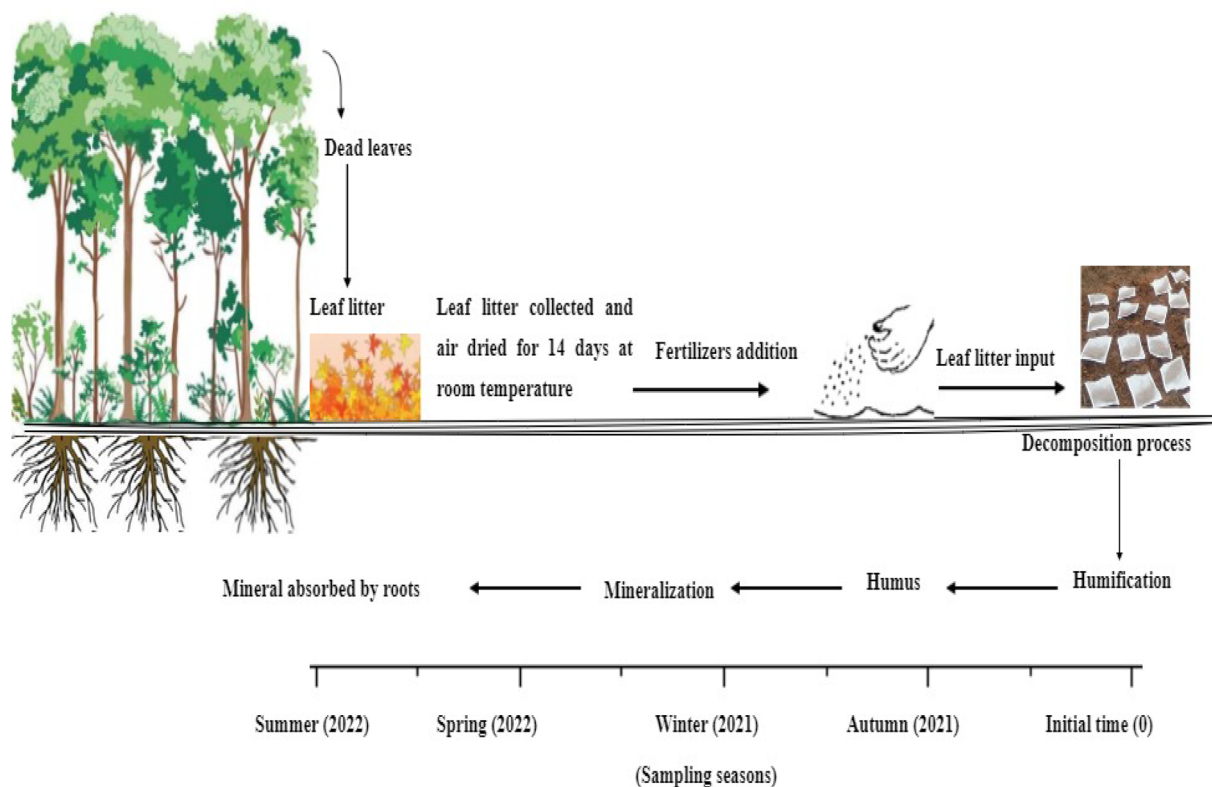
Figure 2. Diagram showing the experimental process in white poplar forest in Qadis district
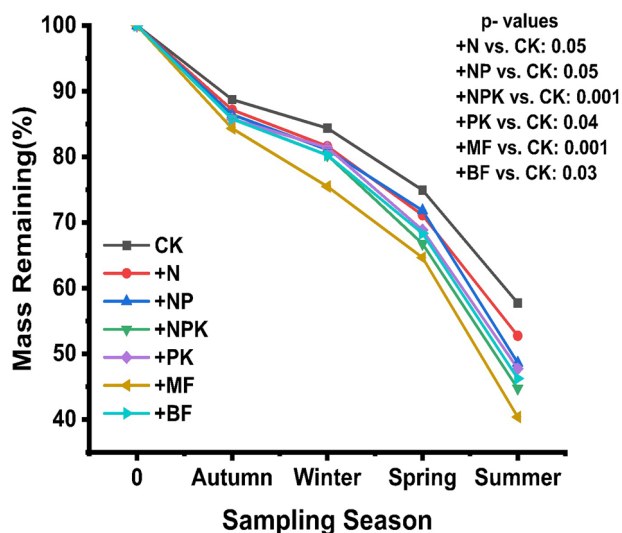

Figure 3. Effect of various fertilizers on leaf litter decompositions at different sampling times. Values are Mean ± SE.

treatments. The remaining mass, from highest to lowest, was as follows: CK (57.73 ± 0.02) %, +N (52.73 ± 0.01) %, +NP (48.63 ± 0.02) %, +PK (47.74 ± 0.01) %, +BF (46.24 ± 0.05) %, +NPK (44.73 ± 0.01) %, and +MF (40.37 ± 0.03) %, respectively. The results from figure 3 revealed that organic and inorganic fertilizer applications significantly increased the leaf litter mass loss, except for nitrogen plots (+N). The leaf litter was primarily much more decomposed in +MF, +NPK, and +BF, respectively (Figure3). The mass loss of white poplar leaf litter over time fitted an exponential equation for CK, +N, +NP, +NPK+PK, +MF, and +BF (R2 = 0.9, 0.91,0.94,0.97,0.96,0.98,0.96). The decomposition constant

K differed among the CK, +N, +NP, +NPK, +PK, +MF, and +BF, with the highest in +MF and the lowest in the CK. The litter decay rate constant (k) followed the order +MF > +NPK > +BF > +PK > +NP > +N > CK (0.56, 0.53, 0.52, 0.51, 0.51,0.5, and 0.46) per year (Table 1).

3.2. Dynamics of C, N, P, and K concentrations in leaf litter under various fertilizer applications

In this study, we examined the dynamics of C, N, P, and K concentrations during the decomposition process. The interaction between fertilizer applications and sampling time resulted in noticeable changes in C, N, P and K concentrations. Our findings indicate a significant decrease in carbon concentration after the first sampling time across all stages of the experiment, with the following order: CK > +N > +NP > +NPK > +PK > +MF > +BF, except for the spring season ($p < 0.05$) (Figure 4a), The N concentration in white poplar exhibited a gradual increase throughout all stages of the experiments, except for the last sampling stage. However, the concentration varied among the different fertilizer treatments in different seasons. In autumn and winter 2021, the nitrogen concentration in white poplar during the decomposition process followed the order: +NPK > +BF > +NP > +MF > +PK > CK and +NPK > +MF > +BF > +NP > +N > +PK > CK, respectively (Figure 4b). In contrast, the N concentration in white poplar during decomposition was highest in the spring and lowest in the summer of 22, reflecting seasonal variation (Figure 4b). Furthermore, the concentration of P in white poplar leaf litter exhibited an increase in autumn 2021 and spring and summer

2022. The order of P concentration, from highest to lowest, was +NPK > +NP > +MF > +BF > +N > CK > PK. Notably, there was a significant difference in P concentration between +NPK and +BF treatments (Figure 4c). However, the concentration K in white poplar leaf litter significantly decreased throughout all periods of the experiment. Comparatively, the concentration of K in white poplar was higher in +NPK, +PK, +MF, +BF,

and +N treatments compared to the control plots (Figure 4d).

3.3. Dynamic characteristics of soil physiochemical properties

The utilization of various fertilizers had a significant impact on the physicochemical properties of the soil,

Table 1. Leaf litter decomposition constant, correlation coefficient, at T50% and T95% decomposition of White poplar leaf litter under various fertilizers. All relationship was significant (***$p < 0.001$)

Treatments	Regression model	Decomposition constant K	Correlation of determination R^2	Time of half decompositon 50%	Time of 95% decomposition
CK	$Y= 101.1761\ e^{0.46t}$	0.46067	0.9	1.50465	6.50299
+N	$Y= 101.6294\ e^{0.504t}$	0.50456	0.91	1.373766	5.937316
+NP	$Y= 102.3906\ e^{0.5104t}$	0.5104	0.94	1.358047	5.869381
+NPK	$Y= 100.925\ e^{0.53098t}$	0.53098	0.97	1.305411	5.641893
+PK	$Y= 101.6294\ e^{0.5101t}$	0.5101	0.96	1.358846	5.872833
+MF	$Y= 100.1906\ e^{0.5606t}$	0.5606	0.98	1.236438	5.343796
+BF	$Y= 100.325\ e^{0.5203t}$	0.5203	0.96	1.332207	5.757702
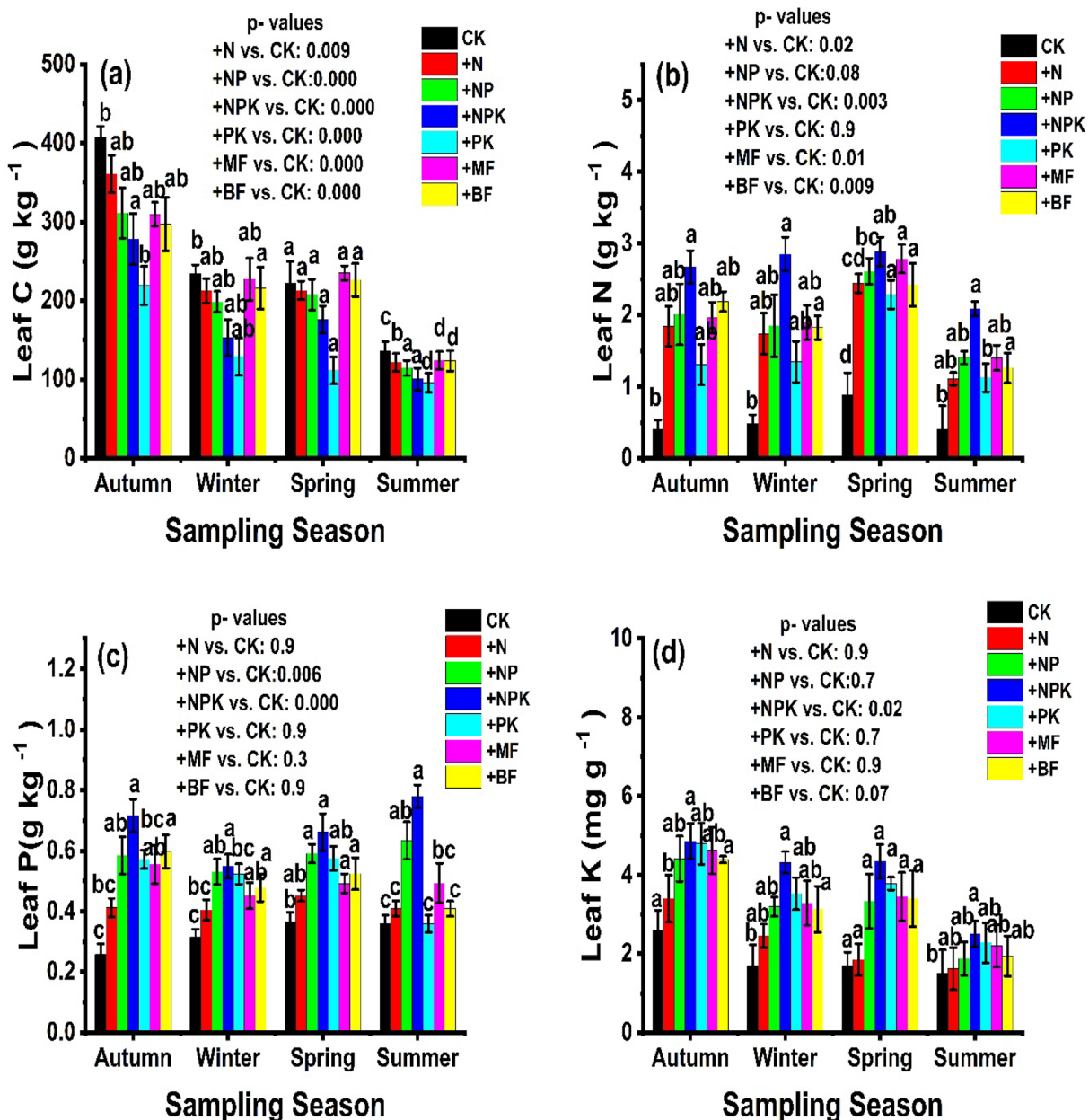
Figure 4. The dynamic of Carbon, Nitrogen, Phosphorus, and Potassium concentration in leaf litter for treatments during the decomposition process at four sampling times (means ± SE), $p < 0.05$.

Table 2. Comparison of physicochemical characteristics of soil in different fertilizer treatments at white poplar forest at four sampling times. Different lower- case letters within columns indicate significant difference among means.

Sampling Season	Treatments	pH	SM (%)	SD (g/cm³)	CP (%)	NCP (%)
Autumn(2021)	CK	$4.36 \pm 0.01a$	$11.33 \pm 2.5a$	$1.21 \pm 0.23a$	$25.05 \pm 8.87a$	$11.03 \pm 5.7a$
	+N	$4.56 \pm 0.05a$	$11.4 \pm 2.1a$	$1.22 \pm 0.4a$	$24.04 \pm 7.82a$	$11.45 \pm 6.4ab$
	+NP	$4.45 \pm 0.06a$	$11.8 \pm 3.1a$	$1.19 \pm 0.32a$	$24.03 \pm 6.43a$	$11.56 \pm 4.2a$
	+NPK	$5.12 \pm 0.2a$	$12.17 \pm 2.6a$	$1.23 \pm 0.26a$	$24.34 \pm 7.23a$	$11.25 \pm 2.7a$
	+PK	$4.42 \pm 0.2a$	$11.5 \pm 2.3a$	$1.16 \pm 0.17a$	$24.23 \pm 7.2a$	$11.16 \pm 4.5a$
	+BF	$4.25 \pm 0.02a$	$11.23 \pm 2.1a$	$1.13 \pm 0.21a$	$24.13 \pm 5.2a$	$11.12 \pm 3.6a$
	+MF	$4.8 \pm 0.04a$	$11.76 \pm 2.2a$	$1.21 \pm 0.2a$	$24.25 \pm 6.7ab$	$11.21 \pm 4.7a$
Winter (2021)	CK	$4.52 \pm 0.02a$	$12.28 \pm 3.1a$	$1.21 \pm 0.24a$	$25.06 \pm 7.43a$	$11.04 \pm 3.4a$
	+N	$5.15 \pm 0.01ab$	$12.3 \pm 2.4a$	$1.21 \pm 0.22a$	$25.07 \pm 6.35a$	$11.26 \pm 4.6a$
	+NP	$5.34 \pm 0.03a$	$12.56 \pm 2.25ab$	$1.23 \pm 0.4a$	$23.98 \pm 6.72a$	$12.08 \pm 2.7ab$
	+NPK	$5.42 \pm 0.02a$	$13.1 \pm 2.12a$	$1.23 \pm 0.32a$	$24.37 \pm 6.65a$	$12.04 \pm 3.5ab$
	+PK	$4.62 \pm 0.01a$	$11.7 \pm 2.1a$	$1.36 \pm 0.14a$	$24.19 \pm 5.23a$	$11.36 \pm 3.23a$
	+BF	$4.45 \pm 0.01a$	$11.43 \pm 2.4a$	$1.33 \pm 0.15a$	$23.33 \pm 5.23a$	$11.32 \pm 2.5a$
	+MF	$5.1 \pm 0.4ab$	$11.96 \pm 2.1a$	$1.41 \pm 0.24a$	$22.35 \pm 2.45ab$	$11.41 \pm 2.4a$
Spring (2022)	CK	$4.79 \pm 0.06a$	$12.56 \pm 2.32a$	$1.23 \pm 0.3a$	$22.25 \pm 7.12a$	$11.23 \pm 4.2a$
	+N	$5.45 \pm 0.02ab$	$12.29 \pm 3.2a$	$1.23 \pm 0.22a$	$23.37 \pm 7.22a$	$11.23 \pm 2.4a$
	+NP	$5.53 \pm 0.03ab$	$12.27 \pm 3.3ab$	$1.12 \pm 0.41a$	$26.47 \pm 7.43ab$	11.27 ± 3.1
	+NPK	$5.58 \pm 0.02a$	$13.44 \pm 2.5ab$	$1.23 \pm 0.32a$	$24.33 \pm 6.22ab$	$11.37 \pm 3.7ab$
	+PK	$4.82 \pm 0.03a$	$11.7 \pm 2.1a$	$1.36 \pm 0.31a$	$24.13 \pm 4.34ab$	$11.36 \pm 3.4a$
	+BF	$4.65 \pm 0.02a$	$11.43 \pm 2.6a$	$1.33 \pm 0.23a$	$23.31 \pm 6.4ab$	$11.32 \pm 2.5a$
	+MF	$5.2 \pm 0.05ab$	$11.96 \pm 2.2a$	$1.41 \pm 0.24ab$	$22.25 \pm 4.6ab$	$11.41 \pm 2.21a$
Summer (2022)	CK	$4.6 \pm 0.01a$	$12.14 \pm 3.5a$	$1.23 \pm 0.22a$	$22.27 \pm 7.52a$	$12.23 \pm 2.7a$
	+N	$5.4 \pm 0.03a$	$12.56 \pm 2.8a$	$1.20 \pm 0.34a$	$26.25 \pm 7.36a$	$12.20 \pm 2.1a$
	+NP	$5.45 \pm 0.01ab$	$13.4 \pm 3.4a$	$1.22 \pm 0.23a$	$26.25 \pm 6.45ab$	$11.25 \pm 3.1a$
	+NPK	$5.49 \pm 0.02ab$	$13.5 \pm 2.6ab$	$1.23 \pm 0.45a$	$24.76 \pm 5.7ab$	$13.46 \pm 3.4ab$
	+PK	$5.02 \pm 0.03a$	$11.7 \pm 2.3a$	$1.36 \pm 0.23a$	$24.33 \pm 5.7a$	$11.36 \pm 2.23a$
	+BF	$4.85 \pm 0.02a$	$11.43 \pm 2.1a$	$1.33 \pm 0.32a$	$23.33 \pm 5.3a$	$11.32 \pm 3.2a$
	+MF	$5.4 \pm 0.04ab$	$13.76 \pm 2.1ab$	$1.43 \pm 0.24ab$	$20.45 \pm 6.25ab$	$11.41 \pm 3.32ab$

Note: Effects of different fertilizers on soil properties. soil pH, SM: soil moisture, SD: soil bulk density, CP: capillary porosity, and NCP: non-capillary porosity

as evidenced by the data presented in (Table 2). In the initial phase of the experiment, which covered autumn and winter 2021, remarkable increase in soil pH were observed in all experimental treatments (+NPK, +MF, +PK + NP, +N). Fertilizer application had a significant effect on soil physical properties, especially soil moisture, capillary porosity and non-capillary porosity in spring and summer 2022. However, no significant difference was detected in soil bulk density that could be attributed to fertilization. In particular, in summer 2022, +NPK had a higher capillary porosity of 26.76%, +NPK had a higher non-capillary porosity of 13.46% and + MF had a higher soil moisture content of 13.76%, as indicated in (Table 2). The assessment of SOC concentration significantly decreased over the year experiment; the concentration of SOC in autumn 2021 in orderly from highest to the lowest (+MF, +NPK, +BF, CK, +NP, +PK, +N), the assessment of SOC in winter 2021 and spring and summer 2022 were respectively from highest to the lowest (+MF, +CK, +NPK, +NP, +PK, and +N) (Figure 5a).

The concentration of TN in the soil exhibited an initial decrease during the first sampling time in winter (2021) followed by consistent decreases in spring and summer (2022). In the autumn of 2021, which marked the initial stage of the experiment, the TN content was notably higher in plots treated with + NP, +NPK, +N, +BF, and + MF compared to the control plots. Specifically, in winter 2021, the TN content ranked highest to lowest as + MF, +BF, +NPK, +NP, +N, +PK, and CK. In the spring and autumn of 2022, the TN content followed a similar trend, with + MF, +BF, +NPK, +NP, +N, +PK, and CK showing decreasing concentrations from highest to lowest, as illustrated in (Figure 5b). The response of soil TP and TK

different fertilizers were varied at first sampling time, and after first sampling time significantly decreased ($p < 0.05$), that the content of soil TP was respectively from highest to the lowest + BF, +NPK, +NP, +MF,+N, +PK, CK in winter (2021), +BF, +NPK, +NP,+MF,+N, +PK, CK in spring (2022), +BF, +NPK, +NP, +MF, +N, +PK, CK in summer (2022) (Figure 5c), while the content of soil TK from highest to the lowest were respectively in + NPK, +PK, +MF, +NP, +BF, +N, CK in winter (2021), +NPK, +PK, +MF,+NP, +BF, +N, CK in spring (2022), +NPK, +PK, +NP, +MF, +BF, +N, CK in summer (2022) (Figure 5d).

3.4. Stoichiometric characteristics of C, N, and P response fertilizer applications

As illustrated in Figure 6a, the ratio of C to N in white poplar leaf litter was highest during the initial sampling stages, specifically in the autumn and winter of 2021, as well as in the summer and spring of 2022. The ratio of C to P concentration in white poplar litter under different fertilizers was highest in autumn, winter (2021), and spring and summer (2022), respectively (Figure 6b). The ratio N to P response to different fertilizers shown in (Figure 6c) significantly varied, which was highest in spring (2022) and winter (2021) and lowest in summer (2022) and autumn (2021), respectively. The ratio C:N in soil shown in (Figure 6d) significantly varied in autumn (2021) and summer (2022) ($p < 0.05$) among the different fertilizer treatments. As shown in (Figure 6e), the ratio of C:P in soil under different fertilizers significantly increased ($p < 0.05$). In contrast, the ratio of N to P concentration in soil varied at different experiment stages in different fertilizer treatments (Figure 6f).
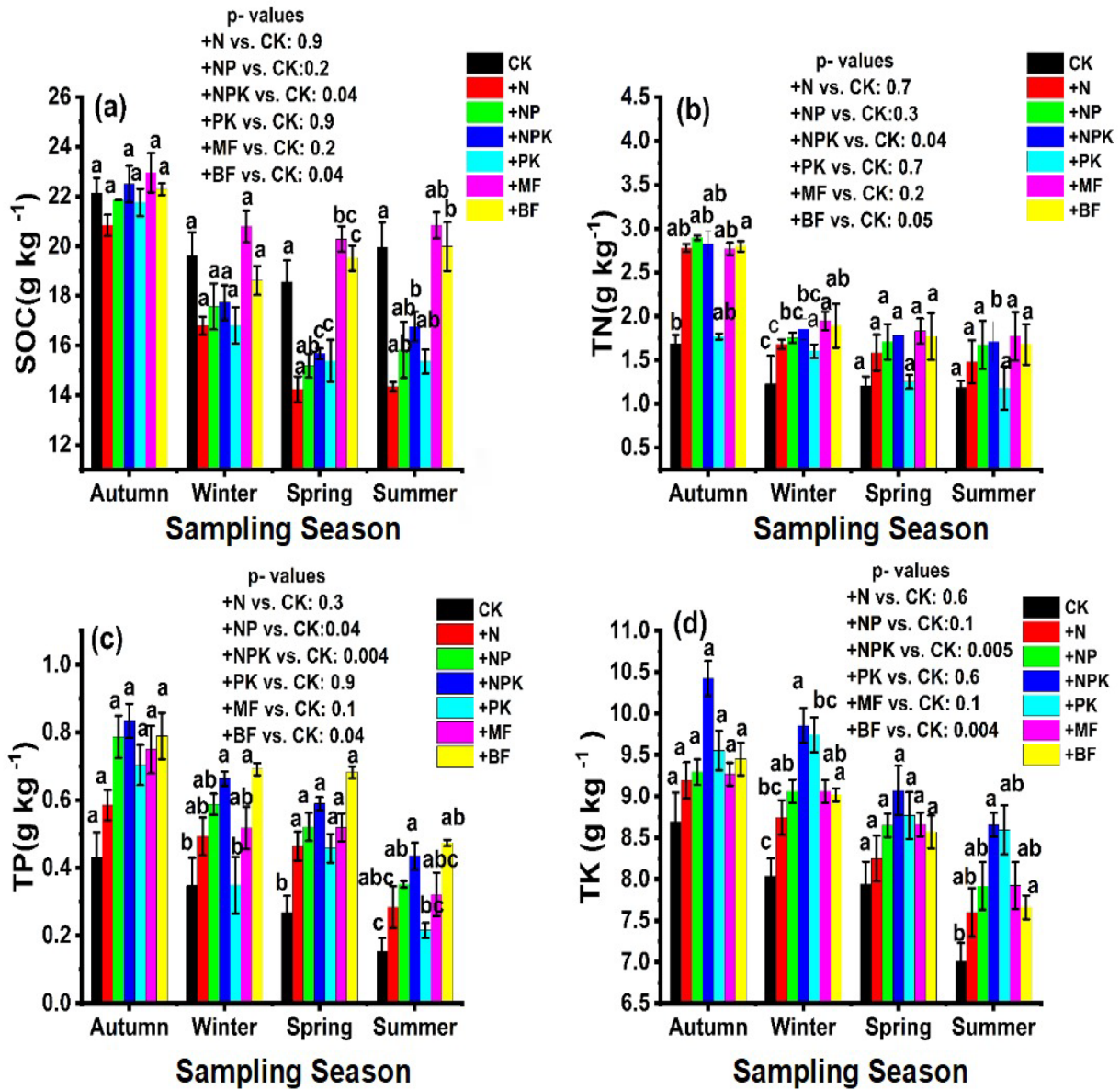
Figure 5. Dynamic characteristics of soil (SOC, TN, TP, and TK) for treatments during the decomposition process at four sampling times (means ± SE), $p < 0.05$.
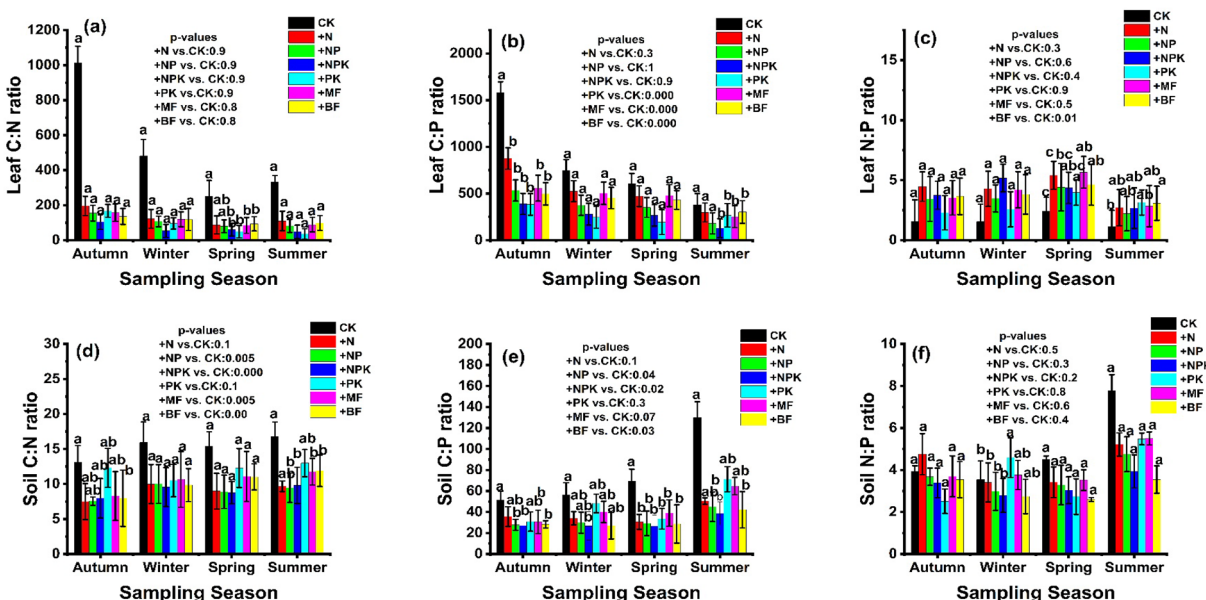

Figure 6. Stoichiometric characteristics of C, N, P, and K in leaf litter and soil for treatments during the decomposition process at four sampling times (means ± SE), $p < 0.05$, $p < 0.01$, $p < 0.001$.

The ratios of C:N in leaf litter under fertilizer treatments at the final stage of the experiment (CK, +N, +NP, +NPK, +PK, +MF, +BF) were 332.58, 109.78, 81.57, 48.18, 35.5, 88. 7, and 98.15, respectively. The C:P ratios in leaf litter under fertilizers at the final stage of the experiment (CK+N, +NP, +NPK, +PK, +MF, +BF) were 379.9, 297.61, 180.67, 128.9, 266.85, 252.07, and 302.25, respectively. The ratios N:P in leaf litter under fertilizers treatments at the final stage of the experiment (CK+N, +NP, +NPK, +PK, +MF, +BF) were 1.14, 2.71, 2.21, 2.67, 3.13, 2.84, and 3.07 respectively. In soil from (CK+N, +NP, +NPK, +PK, +MF, +BF) at the final stage of the experiment, the ratios of C:N were 16.74, 9.68, 9.46, 9.80, 12.9, 11.75, 11.89 respectively. The C:P ratios were 130.16, 50.48, 44.99, 38.57, 71.23, 64.69, 42.17 respectively. The N:P ratios were 7.77, 5.21, 4.75, 3.93, 5.48, 5.5, and 3.54 at the final stage of the experiment, respectively. The differences in white poplar leaf litter C:N, C:P, and N:P ratios, and soil C:N, C:P, and: N:P ratios were positive significant ($p < 0.05$).

3.5. Relationship between the stoichiometric characteristics of C, N, P, and K as well as their concentrations in various fertilizer applications

The associations between C, N, P, and K content in leaf litter and soil from various fertilizer application treatments at four sampling stages are illustrated in Figure 7. A significant positive correlation exists between C, N, P and K in leaf litter ($p < 0.01$, $p < 0.05$). At four sampling stages, additionally, we found a negative association between C, N, P, and K concentration in leaf litter and SOC ($p < 0.01$, $p < 0.05$). Positive associations were found between C, N, P, and K concentrations in leaf litter and soil P and K at four sampling times ($p < 0.01$, $p < 0.05$). Under different fertilizer

treatments, SOC negatively correlated with soil total N, P, and K ($p < 0.05$, $p < 0.01$) at four seasons.

Figure 8 illustrates the correlation between C, N, P, and K in leaf litter and soils and their stoichiometry at four sampling times in different treatments. The results showed that a significant negative relationship was determined between stoichiometric characters of C, N, P and K concentration in leaf litter at four sampling stages, except for the relationship between C concentration and C:P, N:P were found positive. At four sampling stages, strong negative relationships were found between C, N, P, and K concentrations in leaf litter and soil stoichiometry ($p < 0.01$). Additionally, we found there is a positive connection between leaf C:N and soil C:N, C:N < N:P in the first sampling stages, while the relationship between leaf N:P and soil C:N, C:P, N:P were negative ($p < 0.05$).

4. Discussion

4.1. Leaf litter decomposition under various fertilizer treatments

Fertilizers afford important nutrients to plants, including N, P, and K potentially influencing the decomposition practice of leaf litter (Chen et al., 2013; Cissé et al., 2021; Zhang et al., 2021). In this investigation, we found that fertilizer application on leaf litter positively impacted the decomposition rate in the white poplar forest. The decomposition process was accelerated mainly in +MF and +NPK at four samplings, while the impact of nitrogen addition (+N) on decomposition was very slow at all stages of the investigation; this was consistent with earlier studies. (Du et al., 2020; Zhou et al., 2017), which found that the accumulation of organic fertilizers considerably accelerated litter decomposition rates compared to control plots
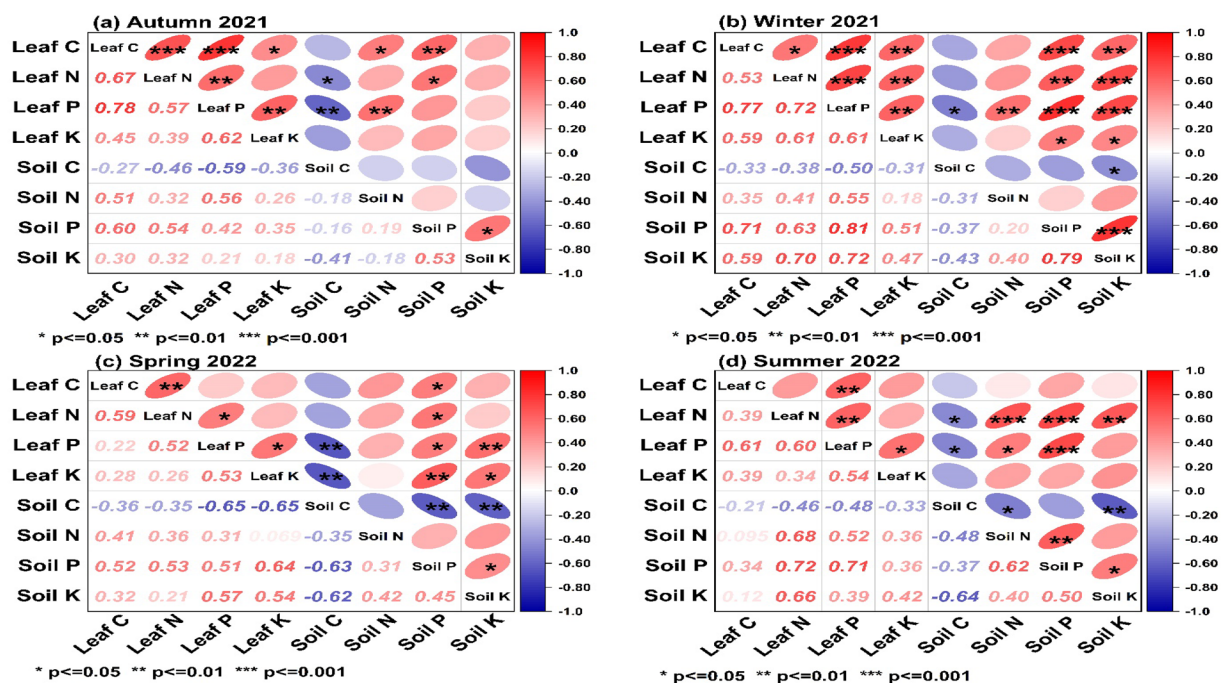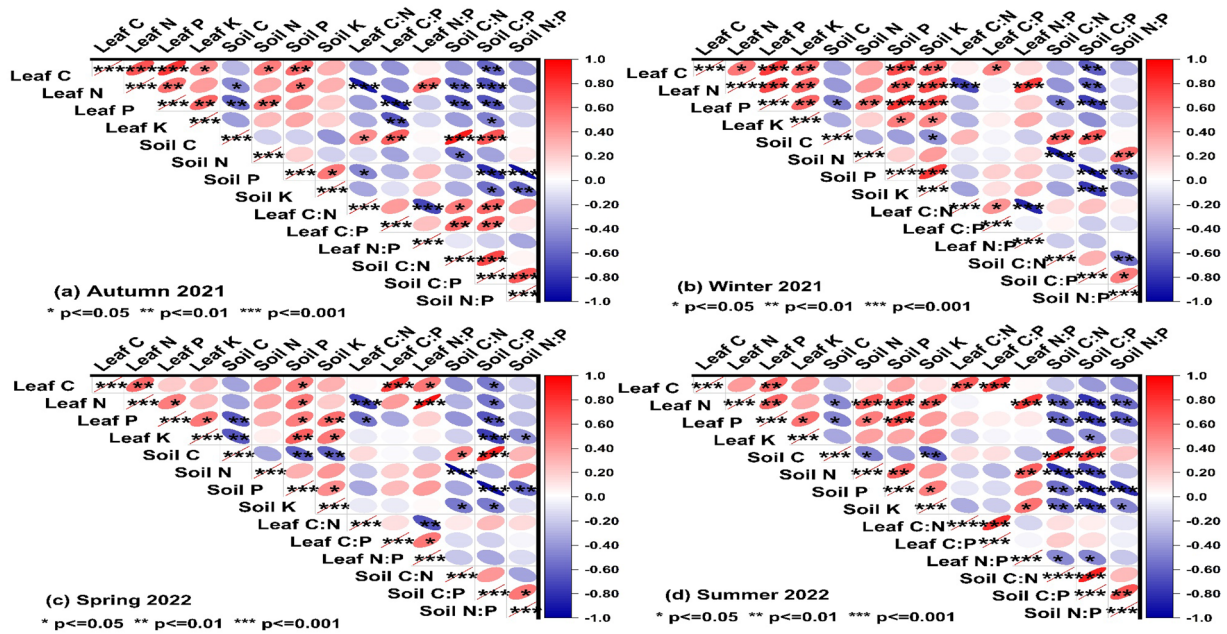

Figure 7. Correlations between C, N, P and K concentration in leaf litter and soil at four sampling stages (means ± SE), $p < 0.05$, $p < 0.01$, $p < 0.001$.

Figure 8. Correlations between C, N, P and K concentration and between their stoichiometric characters at four sampling stages (means ± SE), $p < 0.05$, $p < 0.01$, $p < 0.001$.

(Liu and Wang, 2021; Yu et al., 2015). Nitrogen application can lead to a reduction in soil microbial biomass and alter the microbial community composition, which may contribute to the observed decrease in the decomposition rate. In our study, the application of + MF, +NPK, and + BF fertilizers significantly influenced the decomposition rate of white poplar leaf litter. These treatments notably accelerated the decomposition process, which has not been previously studied in the context of white poplar leaf litter. Previous research has mainly focused on the effect of phosphorus addition, which was found to increase the decomposition of coarse woody debris (CWD) (Chen et al., 2016).

4.2. Effect of different fertilizers on leaf litter nutrient concentration (C, N, P, and K)

The effect of various fertilizers on leaf litter nutrient concentrations, including N, P, and K, were varied, and Typically, the concentration of C and K decreased during the first stage of the experiment, which occurred during leaf litter decomposition. The results from our one-year decomposition experiment revealed that various fertilizer applications and decomposition stages and their interaction are significant factors in understanding the observed variations. Specifically, the different fertilizer applications accelerated the decomposition of leaf litter. However, our results showed that C concentration after the first sampling stages significantly decreased at all stages of the experiment, respectively, from highest to the lowest (CK > +N > +NP > +NPK > +PK > +MF > +BF) except the spring season ($p<0.05$) (figure 4a), The concentration of N in white poplar gradually increased at all stages of the experiments. This can be attributed to the high C:N ratio of the materials used, as their decomposition

released N over time. However, it varied among the fertilizer treatments in different seasons (figure 4b). The concentration of P in white poplar leaf litter exhibited a consistent increase during autumn 2021 and spring and summer 2022, as depicted in figure 4c. These findings provide support for the widely accepted assumption that the availability of nutrients in the soil and the concentration of nutrients in plant tissues are closely interconnected (Elser et al., 2000; W. Zhang et al., 2020). The association between TN and TP concentrations in both leaf and soil has been documented at both the community and species levels. At the community level, elevated atmospheric N deposition is linked with higher plant N concentration in urban areas compared to rural areas. Conversely, in rural areas, P fertilization leads to increased soil P and plant P concentration (Elser et al., 2007; Sardans and Peñuelas, 2015). N fertilization enhanced plant TN concentration at the species level from 18 to 65% in Chinese fir (Xu and Timmer, 1999) and 24% in slash pine (Chen et al., 2010). Similarly, P fertilization resulted in a 20% increase in tissue in slash pine (Hu et al., 2011) and up to 800% in Sitka spruce (Proe and Millard, 1995). However, the concentration of K in white poplar leaf litter significantly reduced in all stages of the experiment; the concentration of K in white polar was greater in + NPK, +PK,+MF,+BF, and + N in comparison to the control plots (figure 4d); this study was in agreement with the previous study (Sardans and Peñuelas, 2015).

4.3. Effect of fertilizers on dynamic characteristics of soil (SOC, TN, TP and TK)

The response of soil nutrients to various fertilizers during the breakdown of leaf litter can be complex and is influenced by various factors. The decomposition

process involves the breakdown of organic matter in leaf litter, releasing nutrients back into the soil, various fertilizers, when applied to the ground, can interact with this process and affect the availability and cycling of nutrients (Fang et al., 2021). In this study, the concentration SOC significantly decreased at + NPK and + BF in comparison to control plots; the concentration of soil TN in white poplar at first sampling time increased and constantly decreased respectively at winter (2021), spring and summer (2022), The response of soil TP and TK different fertilizers were varied at first sampling time, and after first sampling time significantly decreased ($p<0.05$), in our study, the impact of various fertilizer is evident and had a significant effect on soil fertility a prior study suggested that adding mineral fertilizers is advantageous for the soil health; however, an excessive addition of phosphorus can lead to phosphorus fixation which can further decline soil health. Our finding agrees with a previous study (Chen et al., 2015; Liu and Wang, 2021) found that nitrogen fertilization significantly increased soil nitrate and ammonium concentrations, indicating increased mineralization of organic nitrogen during leaf litter decomposition, +NP, +NPK, +BF fertilizers had a significant impact on total phosphors in soil, (Keuskamp et al., 2015) found that nitrogen fertilization significantly increased soil nitrogen concentrations, while phosphorus and potassium fertilization had no significant effect. Our findings indicate that the response of soil nutrients to fertilizers during leaf litter decomposition may be primarily driven by nitrogen availability, while the influence of other nutrients may be more context-dependent or less significant.

4.4. The patterns of leaf litter and soil C, N, and P stoichiometry of white poplar

The stoichiometric ratios C, N, and P in soil and leaf litter serve not only to unveil the interconnected relationships between these components but also to signify the decomposability of leaf litter and the pace of nutrient cycling (Aerts et al., 2012; Ge and Xie, 2017; Güsewell and Verhoeven, 2006). The N:P ratio in leaves serves as a valuable indicator of nutrient-limiting conditions that impact a plant at various growing stages (Wang and Moore, 2014). Tree growth is primarily constrained by N when the N:P ratio below 14, whereas it becomes limited by P when the N:P ratio exceeds 16. Growth is limited by both N and P when the N:P ratio falls within the range of 14 to 16 (Cheng et al., 2022; Huang et al., 2023; Shen et al., 2023). The N:P ratio in leaves from white poplar was <14 at four sampling times; this indicates that N was the constrained factor in the forest ecosystem in the experimental region, potentially attributed to human activities and serious soil erosion. However, there is ongoing judging the determination of critical nutrient dosage using the stoichiometric ratio of elements (Ellison, 2006; Güsewell and Verhoeven, 2006; Wu et al., 2012). The conditions and scale of the study area need to be taken into account when accessing soil nutrients.

The N:P ratio significantly influences litter degradation and nutrient return speed. Faster degradation occurs at lower N: P ratios, while degradation slows when the N: P ratio exceeds 25, indicating conditions conducive to nutrient storage (Chen et al., 2020). The leaf litter's N:P ratio in the white poplar area is <25, crucial for enhancing ecosystem functions like soil erosion mitigation and soil moisture retention. Establishing a bush layer is vital to optimize stand structure, as it promotes higher N:P ratios in leaf litter during subsequent arbor and mixed forest formation. The C:P ratio in leaf litter surpasses both the C:N and N:P ratios, indicating lower N content in the white poplar. In this study, the substantial significance of P is apparent in the lower C:P ratios, impacting plant growth. The variations in C:P ratios within soils were significant across different fertilization groups in the experimental area, indicating a consistent impact level of soil phosphorus in this region. Moreover, while soil P availability in the white poplar area surpassed certain thresholds for ecosystem degradation, it still remained below the global average. The soil N:P ratios proved to be a reliable indicator for predicting nutrient limitation. Notable differences in soil N:P ratios among various fertilization treatments in the white poplar area suggest variations in nutrient limitation types among different plant functional groups. The diminished levels of N and P in soils from the studied areas suggest limitations in these nutrients within the examined regions.

4.5. Relationship between C, N, P and K concentration and between their stoichiometric characters in different fertilizer treatments

This study examines the variations in carbon, nitrogen and phosphorus contents across diverse fertilizer treatments along with their relationships with stoichiometric characteristics. Fertilizers are crucial for maintaining the stability of the forest ecosystem. The elements C, N, P, and K are vital for tree growth, playing significant roles in various processes related to tree growth and behavior. Leaf litter and soil, serving as representative components of biotic and plant factors in the forest ecosystem, exhibit sensitivity to environmental changes (Liu et al., 2010). The changes are determined by the different functions of soil and plant Yang et al. (2014) and their differing C, N, and P ratios. This investigation identified a significant correlation between N and P in both leaf litter and soil and their stoichiometry ($p < 0.01$). While prior studies Niu et al. (2017); Liu and Wang (2021) noted a linear correlation between nitrogen and phosphorus contents in plants and soil, our current investigation revealed a notable correlation among C, N, and P contents in both leaf litter and soil. This correlation is consistent with the stoichiometry observed in Tianshan, China (Xie et al., 2016). The variations that are seen could result from the effects of different plant species, types of fertilizers, growth, types of soil, ecosystems, or human activity on the components that plants contain (Yu et al., 2014).

Similar to this study, Wu et al. (2023) revealed that the C:N and C:P ratios are higher in leaf litter than in soil, with a significant linear relationship ($p < 0.01$) between the stoichiometry and total nitrogen, total phosphorus and total potassium content of leaves were found (Dong et al., 2021). C, N, and P in leaf litter had a significant impact on soil C:N: P ratio stoichiometry characteristics. This emphasizes the contributions of nutrient return within the forest ecosystem as revealed in this study. Strong relationships exist between the carbon, nitrogen, phosphorus and potassium content and their stoichiometry ratios. Reflecting a self-fertilizing aspect within the ecosystem. The white poplar forests we studied are significantly impacted by human activities, including factors like firewood collection, grazing, deforestation and reclamation. However, furthermore, our findings highlight the soil's influences on the carbon to nitrogen to phosphorus ratio under various fertilizers.

5. Conclusions

In conclusion, mineral fertilizers, manure fertilizers, and bird fertilizers greatly affected leaf litter decomposition, the concentration of nutrients, and their stoichiometry. Our study showed that fertilization generally leads to an increase in nutrient concentrations in leaf litter, reflecting the higher nutrient content and accelerated decomposition rates; the decay rate constant (k) shows the decomposition rate of white poplar leaf litter in and orderly + MF > +NPK > +BF > +PK > +NP > +N > CK (0.56, 0.53, 0.52, 0.51, 0.51, 0.5, and 0.46) facilitated by fertilizers; the impact of fertilizer applications on leaf litter is primarily driven by increased nutrient availability, which stimulates microbial activity and enhances the decomposition process. This research presents essential insights into understanding the effect of various fertilizers in leaf litter decomposition and nutrient cycling. However, Further research is needed to explore the implications of long-term fertilizer and potential tradeoffs in different ecosystems.

Author Contributions

All authors contributed to the study conception. Material preparation, data collection and analysis were performed by Monira Fayaz and Abdul Baess Keyhani. The first draft of the manuscript was written by Monira Fayaz and Abdul Baess Keyhani and Professor Yang Guang and other authors commented on the manuscript. All authors read and approved the final manuscript.

Data Availability

Data will be available on request.

Conflicts of Interest

The authors have no conflict of interest in this manuscript.

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