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Effect of Litter Quality on Needle Decomposition for Four Pine Species in Korea

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Abstract: Litter decomposition involves multiple complex processes, including interactions between the physicochemical characteristics of litter species and various environmental factors. We selected four representative pine species in South Korea (*Pinus densiflora* Siebold & Zucc., *Pinus thunbergii* Parl., *Pinus koraiensis* Siebold & Zucc., and *Pinus rigida* Miller) to investigate the decay rate and effects of the physicochemical properties on decomposition. Needle litters were incubated in microcosms at 23 °C for 280 days and retrieved four times in about 70-day intervals. The mass loss showed significant differences among the species and was higher in the order of *P. densiflora* (30.5%), *P. koraiensis* (27.8%), *P. rigida* (26.5%), and *P. thunbergii* (23.6%). The needle litter decomposition showed a negative relationship with the initial surface area, volume, density, cellulose content, and lignin/nitrogen of the litter, and a positive relationship with the initial specific leaf area (SLA), surface-area-to-volume ratio (SA/V), and water- and ethanol-soluble substances. The decomposition rate was highly affected by the physical properties of litter when compared with the initial chemical litter quality, and it was strongly influenced by SLA and SA/V. Accordingly, the physical properties of pine needle litter, especially SLA and SA/V, may be the key factors, and they could be used as predictive indices for the decomposition rate of pine tree litters.

Keywords: needle litter decomposition; conifer; microcosm; physiochemical litter quality; *Pinus*

1. Introduction

Litter decomposition is a key ecological process responsible for the release of nutrients from litter and is controlled by the three main factors of environmental conditions, decomposer community, and substrate quality [1–3]. In general, climate (especially temperature and moisture) governs the decay rates at broad regional scales, whereas initial litter quality variables (carbon/nitrogen, lignin, and nitrogen) are more important in controlling the decay rates at small scales, i.e., within the sites [4]. Many processes of litter decomposition are influenced by physicochemical environments and chemical contents of the leaf litter [4–6]. At a local scale, with an almost constant climate, decomposition is strongly affected by the chemical and physical qualities of the substrate [1,7,8].

In general, initial litter chemical quality, characterized by N and lignin concentrations or C/N and lignin/N, is an important factor that influences the decomposition rate. Especially, decomposition rate has been found to correlate positively with nitrogen [9,10], and it correlates negatively with molecules composed of large carbon chains, such as lignin and cellulose [9–11], and high C/N or lignin/N [8,10,12]. The physical properties of litter, such as the specific leaf area (SLA) or the surface-area-to-volume ratio (SA/V) can also influence decomposition rates. Litter with a higher surface area decompose faster owing to a larger contact area for the decomposers to interact with [13,14]. Especially, SLA has been reported to be positively correlated with the decomposition rate [9,11,15], and leaves with a higher SA/V has been known to decompose faster [1,16].

The genus *Pinus* has approximately 110 species worldwide [17] and is one of the most widely distributed genera of trees in the Northern Hemisphere [18–20]. *Pinus* is ecologically important as a major component of boreal, subalpine, temperate, as well as of arid woodlands [21]. Among the genus *Pinus*, four pine species of *Pinus densiflora* Siebold & Zucc., *P. koraiensis* Siebold & Zucc., *P. rigida* Miller, and *P. thunbergii* Parl. are dominant throughout the Korean Peninsula [18] and occupy about 86.3% of the total coniferous forest area in Korea [22,23]. Compared with broadleaf and mixed forest leaf litter, coniferous leaf litter, such as pine species, decomposes very slowly, owing to its contrast chemical properties such as low nutrient concentrations and high lignin content [24–30]. Litter with high lignin content, low SLA, and low nutrient concentration, such as needle litter, exhibit low degradation rates when all conditions are identical [2,24,25]. However, litter decomposition is difficult to state definitely because the processes are complicated by many factors. Litter decomposition rate influenced by climate condition at a large scale [4,31], but sometimes there are no relationships between litter decomposition rates and climate gradients [31,32]. Berg conducted a climatic transect survey of the decomposition of 14 Norway spruce stands across a regional scale in Sweden from 56 to 66°N and found no effect of climate on rates of decay [32]. Therefore, at least in pine species, the influence of climate on litter decomposition is uncertain, and there is a limited understanding of the factors that affect the rate of litter decomposition in pine species producing low-nutrient litter.

Numerous studies have been performed to investigate the decomposition of various litter types in different forests [2,3,5,13,24,25]. However, there is no sufficient information on the characteristics of litter decomposition between pine species that have relatively poor nutrient content; there are limited studies on the four dominant pine species in Korea with regard to litter decomposition. Most studies on pine forests have focused on the structure and dynamics of plant communities [33–35] or the control of diseases and insect pests [36,37]. Although a few studies on litter decomposition have been conducted in pine forests, there is limited information on the effects of physicochemical litter quality on decomposition of different pine litter species, because these studies contain only a simple description of changes in nutrient elements in decaying litter [38–41]. Moreover, it is difficult to directly compare the results of these studies, because each pine species was independently studied at different times, with varying areas, litter type, and forest floor characteristics [38–46]. Also, it is not clear if the differences in decomposition rate of each type of pine litter is attributable to the kinds of environmental conditions present or the chemical properties of the litter. Therefore experiments with controlled environmental conditions are needed for pine needle litter, which is obtained in a directly comparable manner over a similar area of pine species distribution.

We hypothesized that, all else being equal, the decomposition rates of the pine needle litter representing a narrow range of initial litter quality characteristics (both physical and chemical properties) would be different and that these differences would be affected by the physical and chemical properties of the litter. To test these hypotheses, we conducted a microcosm experiment to investigate the comparative litter decomposition rates and the effect of litter quality on needle litter decomposition of the four pine tree species. We collected the needle litter of these four pine tree species in a pine-dominated forest and performed a decomposition experiment in microcosms with the same temperature and humidity conditions for 280 days to investigate the comparative differences in the needle litter decomposition rates of these species and the effects of their physicochemical properties on needle litter decomposition.

2. Materials and Methods

2.1. Study Species and Litter Collection

In this study, four *Pinus* species were selected: three native species *P. densiflora*, *P. koraiensis*, and *P. thunbergii*, and one introduced species, *P. rigida*. Among them, *P. densiflora* is the most important dominant coniferous tree species in Korea [47], and it occupies the largest area, i.e., more than 25.7% (1.5 million ha) of the forest area in South Korea [22]. *Pinus koraiensis*, which occupies 7.3% (170,905 ha) of the forest area in South Korea [22], is a representative species in northern temperate old-growth forests, and it has been widely planted for wood and pine seeds in Northeast Asia [22,46]. *Pinus rigida* was introduced in 1906 from North America for rehabilitation of degraded forested areas [48], and it occupies 11.1% (259,355 ha) of the forest area in South Korea. It is an important afforestation tree species in forests in Korea [22]. *Pinus thunbergii*, which occupies 8.1% (189,866 ha) of the forest area in South Korea [23], is one of the major constituents of the coastal forests established on sand dunes and ocean-facing mountain slopes in Korea [49].

In November 2014, the freshly fallen needle litter was collected from a pure stand of each species in the North of Ganghwa County (37°45′ N; 126°30′ E) in Incheon Metropolitan City, South Korea. The needle litters of *P. densiflora* and *P. thunbergii* were collected from natural forest, whereas *P. koraiensis* and *P. rigida* leaf litters were collected from plantation forest. The collected litter was dried at 60 °C to a constant mass for use in experiments.

Ganghwa County is located in the mid-western part of the Korean peninsula and is the fourth largest island in Korea. Its total area is about 30,200 ha, of which the forest area is 45%, and the area with elevation 50 m above sea level is very flat and constitutes 70% of the total land area [50]. From 1981 to 2010, the average annual temperature recorded at the Ganghwa meteorological station (elevation 48 m above sea level) is 11.1 °C and the annual precipitation is 1346.7 mm. During the summer (June to August), the average monthly temperature is 22.8 °C, and the monthly precipitation is 808.2 mm. During winter (December to February), the average monthly temperature is −1.8 °C, and the monthly precipitation is 56.5 mm. According to study of Cho [51], the vegetation in this area is divided into 19 community types and consists of secondary forest (92.3% of survey area 11,331 ha) which was *Quercus acutissima* Carruth., *P. densiflor*, and *Quercus. monglica* Fisch. ex Ledeb. communities. Artificial planting in the forest area, including trees such as *Robinia pseudoacacia* L., *P. rigida*, etc., represent 5.4% of the area, and it is less extensive than similar plantings in other cities in the metropolitan area [51]. Organic matter content of the soil is on average 5.5% [50] and soil pH is 4.17, indicating acidic soil [50,51].

2.2. Microcosms and Experimental Design

The microcosm experiment was designed to exclude the environmental characteristics associated with each pine species in order to clearly elucidate the effect of the initial physicochemical properties of needle litter on decomposition. To exclude the influence of variation from each field other than the litter quality of each pine species, all materials, except litter, were sterilized before use to ensure that there was no difference between the soil microbial and animal composition for the four pine species at the initial stage of decomposition.

The microcosms were prepared within 1-L, colorless glass bottles. The bottles were filled with 400 g of washed quartz sand. A nylon mesh (mesh size, 1.2 mm^2) was placed on top of the quartz sand in the bottle to prevent the loss of small litter particles. To maintain constant humidity in the microcosms, distilled water was added to the bottles to 90% of the water-holding capacity of quartz sand. Then, approximately 3 g of dried needle litter was placed on the nylon mesh in the microcosm bottles. Soil from each forest location was suspended in water at a 1:10 ratio and leaf litter was immersed for a few seconds in the suspension to re-inoculate the samples with microbes, after which the samples were placed into the bottles.

A total of 64 microcosms were prepared (four species × four collections × four replicates). All microcosms were incubated in a room at a constant temperature of 23 °C for 280 days and watered every 3–4 days to maintain the moisture content. The temperature was the average summer temperature at Ganghwa meteorological station (see Section 2.1) when litter decomposition is at its most active. Decomposing needle litter in the microcosm was collected four times at approximately 70-day intervals over the incubation period, and 16 microcosms (four replicates per species) were randomly retrieved for sampling and analysis.

2.3. Mass Loss Measurements

The decomposing needle litter retrieved from the microcosms was dried at 60 °C to a constant mass for at least 48 h. The remaining mass of the needle litter was determined as the percentage of retrieved dry mass to initial mass prior to decomposition. The decomposition coefficient k was calculated by non-linear regression based on the single exponential decomposition model as follows [52]:

$$X_t = X_o\, e^{-kt} \quad (1)$$

where X_t is the mass at time t, and X_o is the initial mass. Litter half-life ($t_{0.5}$), which is the time necessary to reach 50% mass loss, was estimated as follows [52]:

$$t_{0.5} = -\ln(0.5)/(k) = 0.691/k \quad (2)$$

2.4. Physical Analysis of the Needle Litter

Fresh needle litter collected from the field was scanned to measure the length (mm), perimeter (mm), cross-section area (mm^2), and surface area (cm^2). The cross-section area was measured by cutting the central part of the needle litter. These values were determined using an image-editing program (ImageJ Version 1.48; NIH, Bethesda, MD, USA; http://rsb.info.nih.gov/ij/). The physical characteristics of the leaf litter were determined to the single needle leaflet. The weight (mg) of a single needle litter was calculated by dividing 3 g of needles by the number of needles. The specific leaf area (SLA; $cm^2 \cdot g^{-1}$) was calculated as the leaf area divided by the dry weight of the needle. The volume (mm^3) of the needle litter was calculated by multiplying length and the cross-sectional area. The density ($mg \cdot mm^{-3}$) was calculated from the weight and volume of the needle litter. The surface-area-to-volume ratio (SA/V) was calculated as the surface leaf area divided by the volume of the needle litter.

2.5. Chemical Analysis of the Needle Litter

The dried litter samples were pulverized using a Wiley mill (Thomas Scientific, Swedesboro, NJ, USA) with a 0.1 mm mesh. Subsequently, 0.5 g of the pulverized samples were used for determining the contents of organic carbon, total nitrogen, lignin, and cellulose. The water-soluble and alcohol-soluble substances were determined only for the initial needle litter using the method described by Berg [53]. Total nitrogen was determined using the Kjeldahl method [54] with a Tecator digestion system (FOSS, Hillerod, Denmark) and Kjeltec 8100 distillation apparatus (FOSS). Lignin and cellulose contents were determined using the acid detergent fiber method, as described by Rowland and Roberts [55].

2.6. Statistical Analysis

The physical and chemical properties and decomposition rate of needle litter were analyzed for statistically significant differences ($p < 0.05$) among the species by using one-way analysis of variance (ANOVA), followed by Duncan's new multiple range test. Linear regression analyses were performed to identify the relationships between the initial physical (surface area, SLA, volume, density, and SA/V) and chemical (carbon, nitrogen, lignin, cellulose, water solubles, ethanol solubles, C/N, lignin/N, and water-soluble and alcohol-soluble substances) properties, and mass loss of needle litter. All statistical analyses were conducted using PASW Statistics 18 software (SPSS Inc., Chicago, IL, USA). In addition, we used non-metric multidimensional scaling (NMDS) to examine the relationships between the decomposing needle litter and initial physicochemical litter quality using meta-multidimensional scaling and envfit functions in the Vegan library of R 2.15.3 (R Development Core Team; http://cran.r-project.org).

3. Results

3.1. Physical and Chemical Properties of Needle Litter

The physical properties and chemical composition of needle litter of the four pine tree species are presented in Table 1, and ANOVA indicated significant differences in both physical and chemical properties according to the species ($p < 0.001$).

Table 1. Initial physical and chemical properties of needle litter of the four pine species (*Pinus*).

	P. densiflora	*P. koraiensis*	*P. rigida*	*P. thunbergii*
Physical properties				
Length (mm)	74.56 ± 4.55 ^{a}	85.85 ± 2.05 ^{b}	90.38 ± 6.53 ^{b}	89.29 ± 12.11 ^{b}
Perimeter (mm)	3.04 ± 0.17 ^{a}	3.13 ± 0.17 ^{a}	4.06 ± 0.12 ^{b}	4.14 ± 0.18 ^{b}
CSA (mm^2)	0.42 ± 0.04 ^{a}	0.36 ± 0.05 ^{a}	0.62 ± 0.04 ^{c}	0.84 ± 0.07 ^{b}
Weight (mg)	12.52 ± 0.77 ^{a}	15.51 ± 1.67 ^{a}	23.67 ± 1.36 ^{c}	39.35 ± 2.14 ^{b}
SAL (cm^2)	2.27 ± 0.22 ^{a}	2.68 ± 0.15 ^{a}	3.66 ± 0.21 ^{b}	3.69 ± 0.53 ^{b}
SLA ($cm^2 \cdot g^{-1}$)	181.26 ± 14.02 ^{b}	175.24 ± 28.02 ^{b}	155.28 ± 15.54 ^{b}	93.65 ± 10.44 ^{a}
Volume (mm^3)	31.36 ± 4.04 ^{a}	30.84 ± 3.77 ^{a}	56.43 ± 4.62 ^{c}	75.16 ± 12.64 ^{b}
Density ($mg \cdot mm^{-3}$)	0.40 ± 0.04 ^{a}	0.51 ± 0.11 ^{a}	0.42 ± 0.05 ^{a}	0.53 ± 0.07 ^{a}
SA/V	72.55 ± 2.29 ^{ab}	87.56 ± 5.30 ^{b}	65.00 ± 2.08 ^{ab}	49.37 ± 2.20 ^{a}
Chemical properties				
Carbon (%)	44.77 ± 0.01 ^{b}	44.31 ± 0.32 ^{a}	44.19 ± 0.14 ^{a}	44.15 ± 0.21 ^{a}
Nitrogen (%)	0.46 ± 0.01 ^{b}	0.69 ± 0.03 ^{d}	0.40 ± 0.01 ^{a}	0.49 ± 0.01 ^{c}
Lignin (%)	23.02 ± 0.64 ^{a}	30.95 ± 0.84 ^{c}	23.93 ± 0.53 ^{a}	28.73 ± 0.45 ^{b}
Cellulose (%)	22.77 ± 0.45 ^{a}	24.06 ± 1.09 ^{b}	24.72 ± 0.37 ^{b}	27.78 ± 0.74 ^{c}
C/N	96.80 ± 1.52 ^{c}	63.97 ± 3.13 ^{a}	110.58 ± 1.79 ^{d}	89.68 ± 1.97 ^{b}
Lignin/N	49.77 ± 1.57 ^{b}	44.71 ± 2.99 ^{a}	59.88 ± 2.27 ^{c}	58.35 ± 1.29 ^{c}
Water solubles (%)	3.78 ± 0.83 ^{b}	0.85 ± 0.11 ^{a}	3.51 ± 0.62 ^{b}	1.44 ± 0.05 ^{a}
Ethanol solubles (%)	11.97 ± 0.52 ^{d}	6.44 ± 0.57 ^{b}	7.55 ± 0.57 c	3.76 ± 0.55 ^{a}

CSA, cross-sectional area; SAL, surface area of leaf; SLA, specific leaf area; SA/V, surface-area-to-volume ratio. Physical properties are for the single needle in the fascicle of pine leaves. Values are mean ± standard deviation. Different lowercase letters in the same row indicate differences at $p < 0.001$ (Duncan's new multiple range test).

The needle litters of *P. densiflora* and *P. koraiensis* were characterized by shorter length, lesser thickness, smaller SAL, and higher SLA. In contrast, the needle litter of *P. thunbergii* was characterized by longer length, greater thickness, larger leaf area, and lower SLA. The physical properties of *P. rigida* were intermediate between *P. densiflora* and *P. thunbergii*, and its SAL was larger than that of *P. densiflora* and *P. koraiensis*. The needle litter density was not significantly different among the four pine species.

The chemical composition of needle litter was peculiar to the pine species, but it did not show a consistent pattern according to the pine species (Table 1). The chemical properties of *P. densiflora* litter were characterized by lower nitrogen (0.46%), lignin (23.02%), and cellulose (22.77%) contents and the highest water-soluble substances (3.78%) and ethanol-soluble substances (11.97%) among the pine species. The needle litter of *P. koraiensis* was characterized by higher nitrogen (0.69%) and lignin (30.95%) contents and the lowest water-soluble substances (0.85%). The needle litter of *P. rigida* was characterized by relatively lower lignin contents (23.93%), higher water-soluble substances (3.51%), and the lowest nitrogen concentration (0.40%). In the *P. thunbergii* litter, the nitrogen content and water-soluble substances were lower, lignin and cellulose contents were higher, and the ethanol-soluble substances were the lowest among the four pine species. Both C/N and lignin/N values were the lowest in *P. koraiensis* (63.97 and 44.71, respectively) and the highest in *P. rigida* (110.58 and 59.88, respectively).

3.2. Decomposition Rate and Related Needle Litter Traits

After 280 days of decomposition at 23 °C and constant humidity conditions, the mass losses of the needle litter were reduced by 30.5%, 27.8%, 26.5%, and 23.6% of the initial masses for *P. densiflora*, *P. koraiensis*, *P. rigida*, and *P. thunbergii*, respectively (Figure 1). Moreover, one-way ANOVA of the remaining mass at the end of the experiment showed significant differences among the pine tree species (Figure 1b).

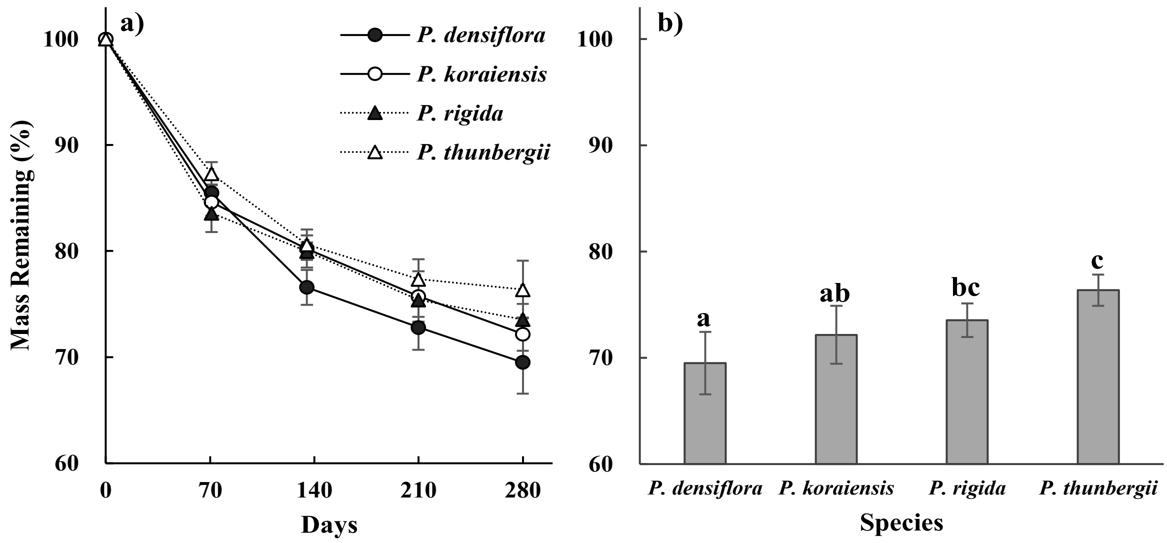

Figure 1. Changes in the mass of needle litter (**a**) and comparison of remaining mass of needle litter after 280 days (**b**) for the four *Pinus* species at 23 °C in the microcosms ($n = 4$). Different lowercase letters above the bars indicate differences at $p < 0.01$ (Duncan's new multiple range test).

The decomposition coefficient (k) of the needle litter of the four pine tree species ranged between 0.474 in *P. densiflora* and 0.352 in *P. thunbergii*, and the half-life ranged between 1.46 years in *P. densiflora* and 1.97 years in *P. thunbergii* (Table 2).

Table 2. Decomposition coefficient k and half-life (50% decomposition) of needle litter of the four *Pinus* species after a decomposition period of 280 days at 23 °C in the microcosms ($n = 4$).

	P. densiflora	*P. koraiensis*	*P. rigida*	*P. thunbergii*
Decomposition coefficient, k	0.474	0.425	0.401	0.352
Half-life (years)	1.46	1.63	1.73	1.97

Half-life was calculated as described by Olson [52].

3.3. Changes in the Chemical Composition During Decomposition

In the decomposing needle litter, the remaining carbon showed a similar pattern with the remaining mass of the decomposing needle litter, and it decreased during decomposition (Figure 2a). The nitrogen content of each decaying litter species was well retained, with some amplitude in the litter of *P. densiflora, P. koraiensis,* and *P. rigida.* However, the nitrogen content of decaying *P. thunbergii* litter decreased according to the litter decomposition. The lignin content of the decaying litter increased at the beginning of decomposition. In *P. densiflora* and *P. rigida*, the lignin content increased by 150–170% of the initial content, and in *P. koraiensis* and *P. thunbergii*, 120–130% (Figure 2c). The remaining cellulose content in all pine species gradually decreased throughout the decomposition period (Figure 2d). The cellulose content decreased most slowly in *P. koraiensis* and the fastest in *P. densiflora*. The C/N and lignin/N values showed opposite patterns in that C/N decreased and lignin/N increased in all the species during the decomposition period (Figure 2e,f). *P. koraiensis*, with high nitrogen and lignin contents in the needle litter, showed different values with another needle species but exhibited the same pattern with another pine species.

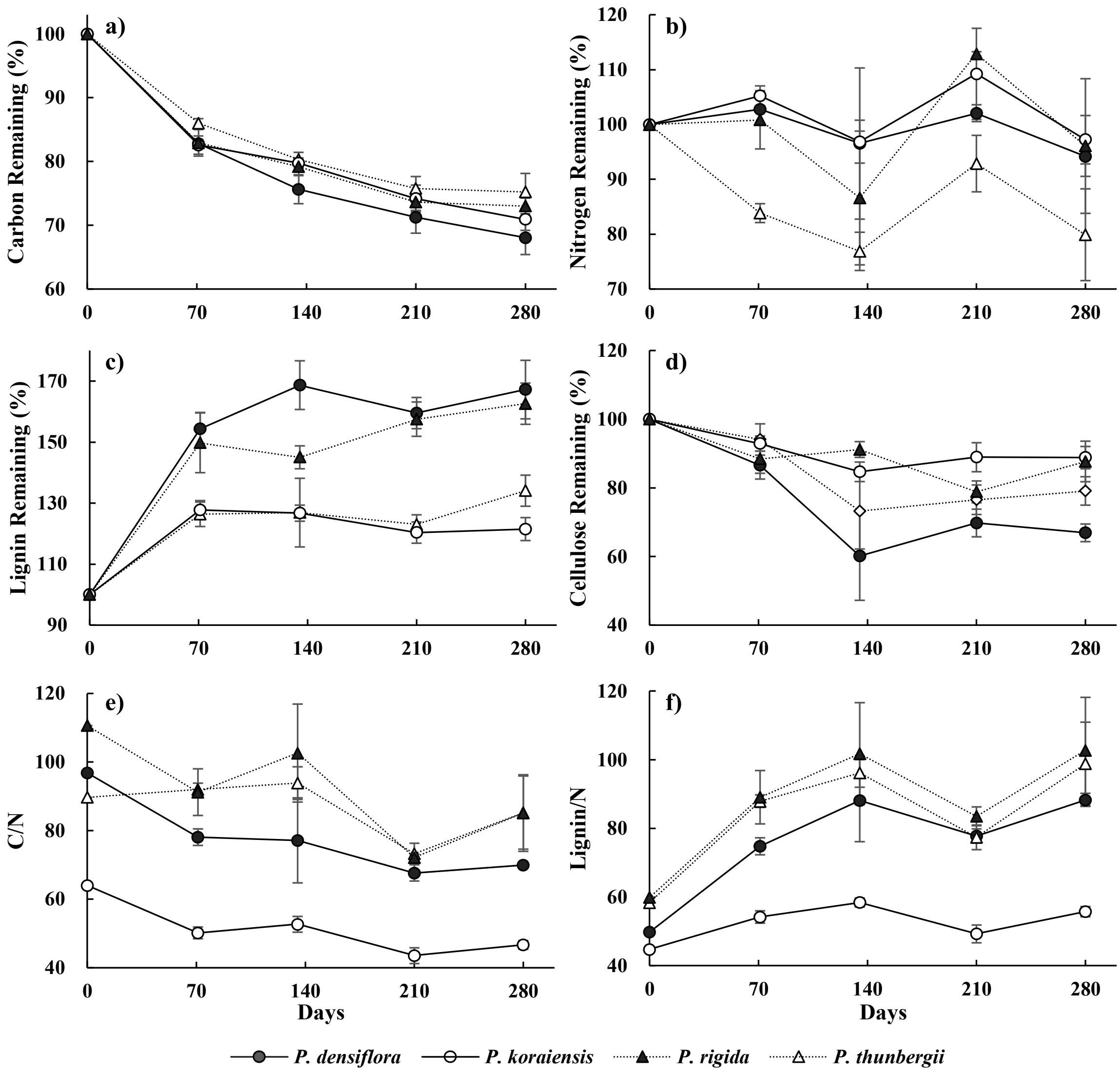

Figure 2. Changes in the remaining (**a**) carbon, (**b**) nitrogen, (**c**) lignin, (**d**) cellulose, (**e**) carbon/nitrogen (C/N), and (**f**) lignin/nitrogen (lignin/N) of the needle litter of the four *Pinus* species during a decomposition period of 280 days at 23 °C in the microcosms (n = 4).

3.4. Factors that Affect Needle Litter Decomposition

The mass loss of pine needle litter was positively correlated with SLA and SA/V and negatively correlated with SAL, volume, and density of needle litter for each pine species and between species. However, the relationships between litter mass loss and litter chemical properties showed different patterns. The typical indices of litter decomposition, such as nitrogen, lignin, C/N, and water-soluble substances, showed positive or negative relationships with mass loss within each species level, but had low determinant coefficients or did not show a significant correlation with mass loss between pine species. In other words, N did not show statistically significant correlation with mass loss between pine species, and the pine species litter with a high content of nitrogen certainly did not decay faster than the litter with lower nitrogen content; identical results were obtained for lignin content and C/N. However, the initial contents of cellulose, ethanol-soluble substances, and lignin/N showed high determinant coefficients between litter species (Figure 3).

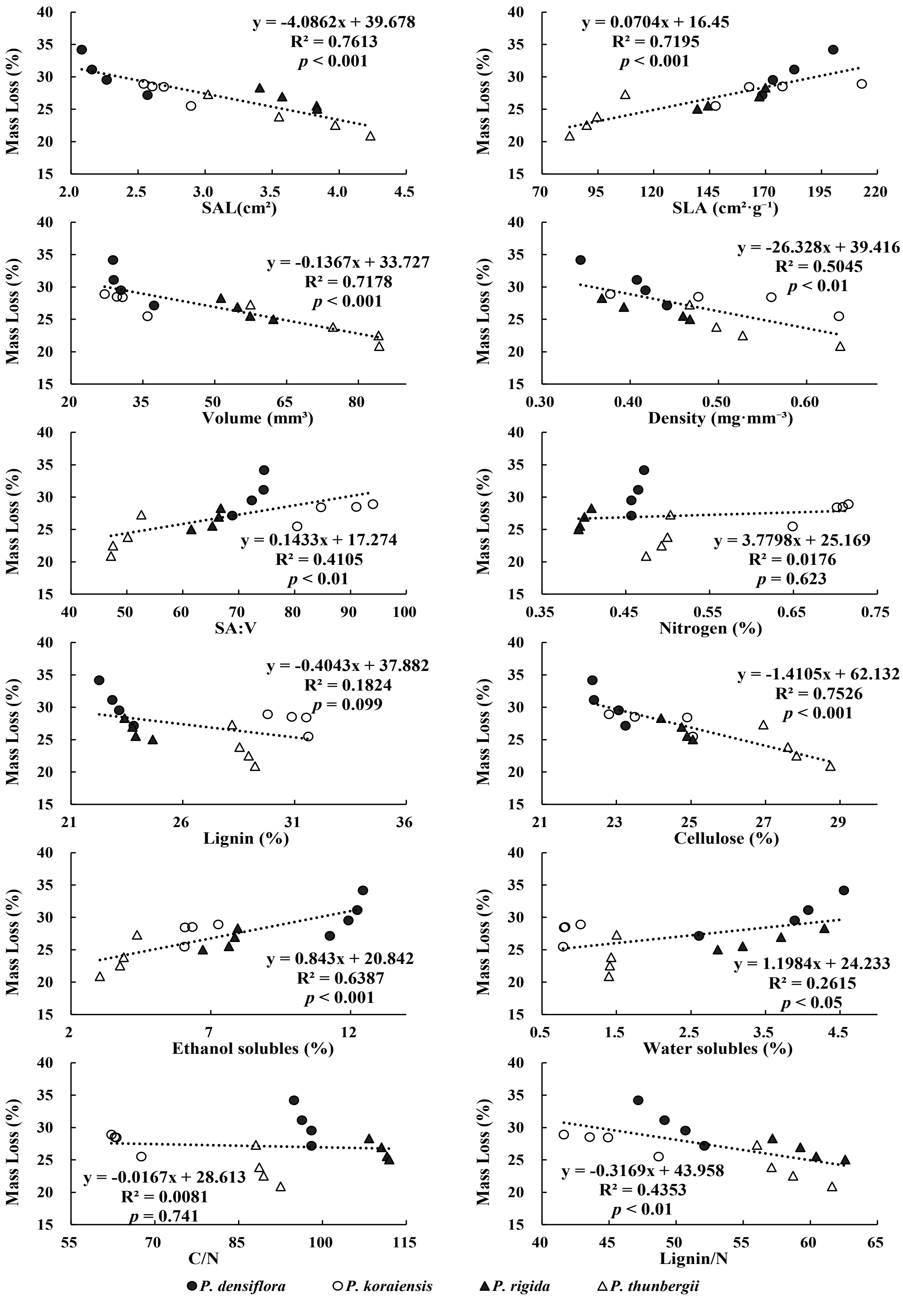

Figure 3. Relationships between the mass loss of needle litter and initial physical (surface area of leaf (SAL), specific leaf area (SLA), volume, and density) and chemical (nitrogen concentration, contents of lignin and cellulose, water-soluble substances, ethanol-soluble substances, C/N, and lignin/N) factors for the four *Pinus* species during a decomposition period of 280 days at 23 °C in the microcosms ($n = 16$).

The NMDS analysis of the relationships between the decomposition of needle litter and the physical and chemical properties showed strong correlations with SAL, SLA, volume, SA/V, cellulose, lignin/N, and ethanol-soluble substances, and weak correlations with density, nitrogen, lignin, C/N, and water-soluble substances. Especially, SAL, volume, and SA/V of the needle litter were statistically significant ($p < 0.05$); the surface area and volume showed a negative correlation, whereas SA/V showed a positive correlation (Figure 4).

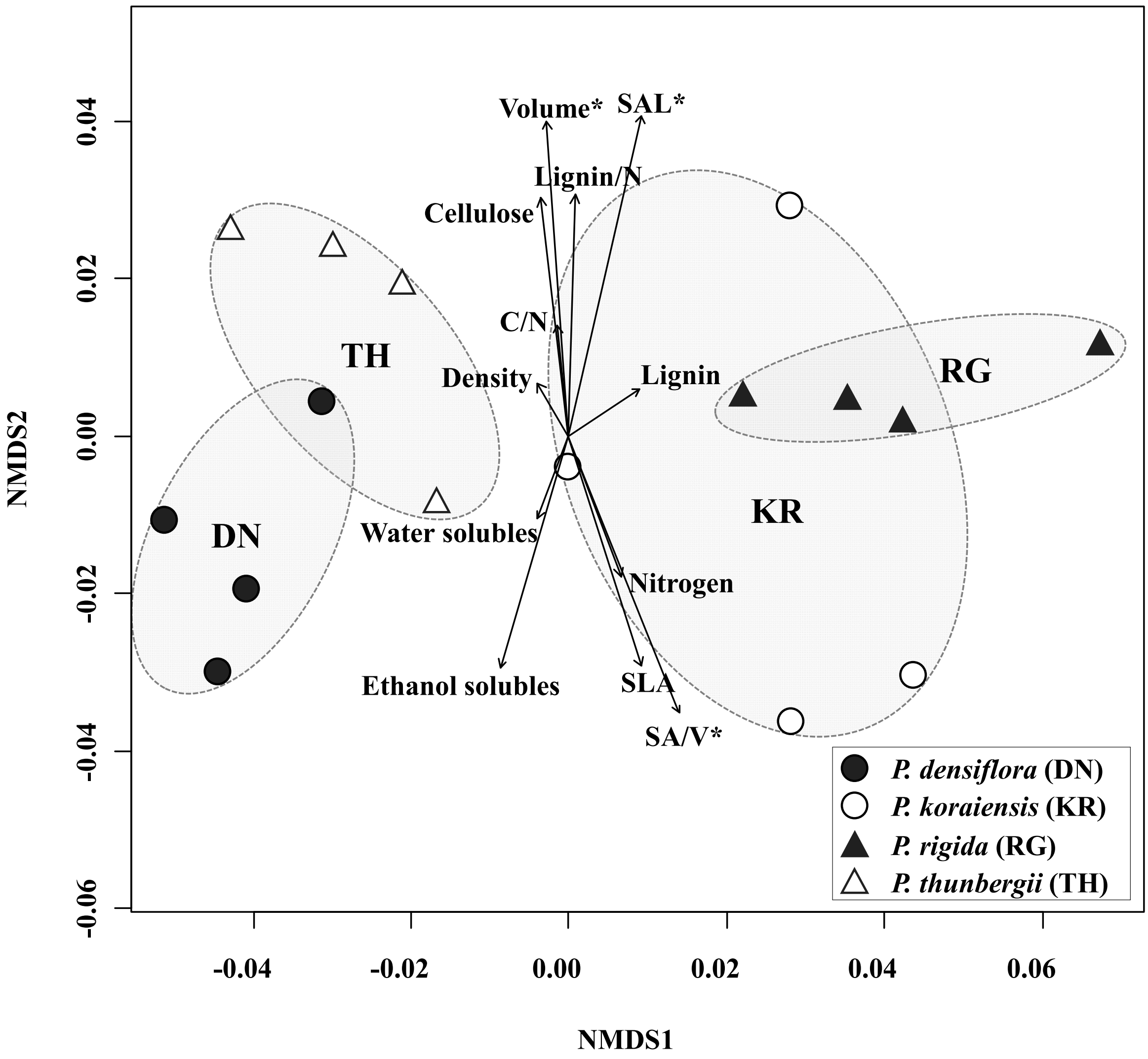

Figure 4. NMDS (Non-metric multidimensional scaling) ordination between the mass loss of needle litter of the four *Pinus* species and initial physical and chemical factors during a decomposition period of 280 days at 23 °C in the microcosms. Arrow direction indicates the correlation slope, and arrow length indicates the strength of the influence of the factors on the decomposition of needle litter. * $p < 0.05$. See abbreviations in Table 1.

4. Discussion

4.1. Difference in Decomposition Rate between Pine Species

In this study, the decomposition rates (k ranged from 0.352 to 0.474) of the pine needle litters were significantly different on the basis of the species and were faster than those reported in other studies of needle litters of the same pine tree species. Chang and Park [38] used the same four pine species (*P. densiflora*, *P. koraiensis*, *P. rigida*, and *P. thunbergii*) and reported k values of 0.108–0.256. Their different findings were probably because our experiment was conducted under constant and stable conditions in the microcosms, and not in the field where the experiment could be seasonally affected. In other studies, the *k* values for each individual pine species ranged from 0.108 to 0.256 for *P. densiflora* [38,40], 0.148 to 0.400 for *P. koraiensis* [38,41,46], 0.191 to 0.262 for *P. rigida* [38,39,41], and 0.133 to 0.177 for *P. thunbergii* [38]. Previous studies indicated that decomposition varies between species and is affected by physical and regional factors [56]. Although the decomposition rate in our study was similar to that observed by You et al. [42] for *P. koraiensis* (*k* value: 0.40) and *P. rigida* (*k* value: 0.37) in a planted pine forest [42], the study was not conducted to reveal significant relationships between the degradation rate and litter quality.

4.2. Influence of Chemical Factors on Needle Litter Decomposition

The chemical properties of the initial litter showed statistically significant differences between pine species (Table 1), whereas they did not show a significant correlation with mass loss between pine species, or low determinant coefficients even when showing significant correlation (Figure 3). In general, the contents of nitrogen and lignin, which are the most common factors that affect the decomposition rate, had the opposite effect on decomposition [9,10]. In this experiment, nitrogen and lignin contents were the highest in *P. koraiensis*, and the values did not show a uniform pattern in the other species. The initial litter quality varies with the plant species, and it causes clear variations in the chemical composition of the newly shed needle litter in different years [57].

These results of the chemical properties suggest that it would be difficult to identify a certain tendency of chemical properties among pine species owing to low nutrient content of the litter. The water-soluble substances in the litter were used as the main energy source by the decomposers, and they are the first to be lost at the early stage of decomposition [1]; it can be concluded that litters with high levels of water-soluble substances can increase the activity of microorganisms [58]. In the early stages of decomposition, the content of water- and ethanol-soluble substances affected decomposition to a greater extent than the lignin content, which is an important factor of litter decomposition [59]. Especially, the content of ethanol-soluble substances showed a high positive correlation ($R^2 = 0.6387$, $p < 0.001$) with the decomposition rate.

In general, the decomposition rate has been found to correlate positively with nitrogen [9,10], negatively with lignin and cellulose [9–11], and highly with C/N or lignin/N [8,12,60]. In this study, however, decomposition rates between the pine species were not correlated with the initial chemical litter qualities of needle litter, such as nitrogen and lignin contents and C/N values. In general, nitrogen and lignin contents and C/N values of initial litter were critical factors that affected litter decomposition, but they did not show any significant relationships with mass loss. Among the initial litter chemical qualities, cellulose and lignin/N were negatively correlated and water- and ethanol-soluble substances were positively correlated with the decomposition rate. These results are in agreement with the results of Berg and Staaf [61], who studied decomposing Scots pine needle litter. The weak relationship between initial nitrogen and decomposition rate reflect the fact that nitrogen is partly stored in litter in forms that are unavailable to microorganisms that first invade the litter. Moreover, Berg and Theander [62] reported that about 1/3 of the total nitrogen is initially complexed to the lignin fraction in Scots pine needles, and such nitrogen is then not readily available to the microorganisms that start the decomposition process. In addition, the correlation between lignin/N and mass loss may be significant even if the correlation between either lignin or nitrogen alone and mass loss is not significant [57].

4.3. Influence of Physical Factors on Needle Litter Decomposition

In the present study, analyses of the needle litter showed that physical properties such as SAL, SLA, volume, and SA/V as well as chemical properties differed significantly among the pine tree species. The needle litter of *P. densiflora* and *P. koraiensis* showed shorter length, less thickness, lower weight, smaller SAL, higher SLA, and lower volume than the needle litters of *P. rigida* and *P. thunbergii*. Overall, the physical properties of the needle litters were higher in the order of *P. thunbergii*, *P. rigida*, *P. koraiensis*, and *P. densiflora* (Table 1). Interspecific differences in the physical properties of needle litter partly coincide with those reported in other studies [63,64]. Lee [63] reported that the length of the leaves was longer in the order of *P. rigida* (range of 7 to 18 cm), *P. thunbergii* (range of 9 to 14 cm), *P. koraiensis* (range of 7 to 12 cm), and *P. densiflora* (range of 8 to 9 cm). The results of Kim [64], who conducted a study to establish taxonomic problems through the needles' morphological characters (e.g., needle length, width, and thickness), are consistent with those of our study. Moreover, SA/V was the lowest in *P. thunbergii*, followed by *P. rigida*, *P. koraiensis*, and *P. densiflora*, and slower litter decay was expected because of the relatively smaller contact area.

The differences in decomposition rates among the pine needle litter can be attributed partly to differences in litter properties, such as the physical and chemical qualities [13]. Gallardo and Merino [14] reported that there is a high correlation between the physical properties and decomposition rates of litter as well as the chemical composition of the litter. Especially, SLA has been reported to be positively correlated with the decomposition rate [9,11,15]. These results are in agreement with the results of this experiment, which showed that the SLA of litter leaves was highly correlated with the decomposition rate of the leaves (Figure 3). However, other physical properties, except SLA, have received far less attention regarding their relationship with decomposition. Especially, volume, density, and SA/V of needle litter were highly correlated with the decomposition rate in this study. These are also consistent with the results that leaves with a higher SA/V decompose faster because of a relative larger contact area for decomposition [1,16]. This indicates that the structural characteristics of needle litter influence the decomposition of needle litter.

Coefficients of determination (R^2) between initial litter qualities and mass loss of each pine tree species showed that physical factors such as SLA, density, and SA/V were higher than the chemical composition, except cellulose with the highest R^2 value (Figure 3). Furthermore, NMDS analysis of the relationships between mass loss throughout the experimental period and initial litter qualities, including physical and chemical properties, of the pine species showed that physical factors, especially SA/V affected decomposition more strongly than chemical factors (Figure 4). Overall, these results indicate that the physical structure of litter with similar physical structure and low litter quality, such as needle litter, is likely to affect the decomposition rate as much as chemical properties.

Globally, low decomposition rate in pine forests gradually increases the accumulation of needle litter on the forest floor [65,66], which has serious implications for bio-geochemical cycling and energy flow in the ecosystem [67]. Accumulation of such organic matter on the forest floor could affect the species diversity in the forest soil and on the forest floor by allelopathic effects or soil acidification [68–70], and forest fires as increase of major source [71]. Moreover, the C dynamics closely related to needle litter decomposition have been affected by forest management [72–74]. Therefore, the decomposition rate of pine needles of each species could be used to predict the implications for the management of the different pine forests.

5. Conclusions

The present study demonstrated that, in the temperate forests of the Northern Hemisphere, decomposition of pine needle litter is largely affected by physical properties of the litter comparable to initial litter chemical quality. The mass loss of needle litter showed a negative relationship with the initial SAL, volume, and density and a positive relationship with the initial SLA and SA/V. Especially, SLA was positively correlated with the decomposition rate of needle litter. In addition, although limited to this study period, a highly positive relationship between SA/V and mass loss was observed throughout the decay experiment. This was probably because needle litter with higher surface area of leaves to weight or volume decompose faster with a relative larger contact area for decomposers. These results suggest that physical factors greatly influence decomposition by decreasing the chance of microorganism activity for degradation because of pine needle litters with low litter quality and surface area.

Thus, the physical properties of needle litters, especially SLA and SA/V, are key factors in the decomposition of pine needle litter and may be used as predictive indices to estimate the decomposition rate of pine tree species. Moreover, analysis of physical properties is economical in terms of time and cost for the prediction of the decay rate of needle litter when compared with the chemical methods. However, except for a few studies, decomposition studies, to a large extent, have overlooked the effects of physical properties of the litter or leaves. Therefore, it is necessary to reflect on not only the chemical composition but also on the physical properties of litter quality as factors that affect decomposition.

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