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RESEARCH ARTICLE

Decomposition dynamic of two aquatic macrophytes *Trapa bispinosa* Roxb. and *Nelumbo nucifera* detritus

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Abstract

In freshwater ecosystems, aquatic macrophytes play significant roles in nutrient cycling. One problem in this process is nutrient loss in the tissues of untimely harvested plants. In this study, we used two aquatic species, *Nelumbo nucifera* and *Trapa bispinosa* Roxb., to investigate the decomposition dynamics and nutrient release from detritus. Litter bags containing 10 g of stems (plus petioles) and leaves for each species detritus were incubated in the pond from November 2016 to May 2017. Nine times litterbags were retrieved on days 6, 14, 25, 45, 65, 90, 125, 145, and 165 after the decomposition experiment for the monitoring of biomass loss and nutrient release. The results suggested that the dry masses of *N. nucifera* and *T. bispinosa* decomposed by 49.35–69.40 and 82.65–91.65%, respectively. The order of decomposition rate constants (k) is as follows: leaves of *T. bispinosa* (0.0122 day^{-1}) > stems (plus petioles) of *T. bispinosa* (0.0090 day^{-1}) > leaves of *N. nucifera* (0.0060 day^{-1}) > stems (plus petioles) of *N. nucifera* (0.0030 day^{-1}). Additionally, the orders of time for 50% dry mass decay, time for 95% dry mass decay, and turnover rate are as follows: leaves < stems (plus petioles) and *T. bispinosa* < *N. nucifera*, respectively. This result indicated that the dry mass loss, k values, and other parameters related to k values are significantly different in species- and tissue-specific. The C, N, and P concentration and the C/N, C/P, and N/P ratios presented the irregular temporal changes trends during the whole decay period. In addition, nutrient accumulation index (AI) was significantly changed depending on the dry mass remaining and C, N, and P concentration in detritus at different decomposition times. The nutrient AIs were 36.72, 8.08, 6.35, and 2.56% for N; 31.25, 9.85, 4.00, and 1.63% for P; 25.15, 16.96, 7.36, and 6.16% for C in the stems (plus petioles) of *N. nucifera*, leaves of *N. nucifera*, stems (plus petioles) of *T. bispinosa*, and leaves of *T. bispinosa*, respectively, at the day 165. These results indicated that 63.28–97.44% of N, 68.75–98.37% of P, and 74.85–93.84% of C were released from the plant detritus to the water at the day 165 of the decomposition period. The initial detritus chemistry, particularly the P-related parameters (P concentration and C/P and N/P ratios), strongly affected dry mass loss, decomposition rates, and nutrient released from detritus into water. Two-way ANOVA results also confirm that the effects on the species were significant for decomposition dynamics (dry mass loss), nutrient release (nutrient concentration, their ratios, and nutrient AI) ($P < 0.01$), and expected N concentration ($P > 0.05$). In addition, the decomposition time had also significant effects on the detritus decomposition dynamic and nutrient release. However, the contributors of species and decomposition time on detritus decomposition were significantly different on the basis of their F values of two-way ANOVA results. This study can provide scientific bases for the aquatic plant scientific management in freshwater ecosystems of the East region of China.

Keywords Aquatic plants · Decomposition rates · Detritus · Nutrient accumulation index · Release

Introduction

Aquatic macrophytes are often considered as the most important biological component in freshwater ecosystems. Their potential in freshwater ecosystems include direct uptake and assimilation of N and P by plant uptake, release of O and organic substances through the root activities, and provide C and nutrients for microbial processes (Jenssen et al. 1993; Ellis et al. 1994; Engelhardt and Ritchie 2002; Maltais-

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Landry et al. 2009; Zhang et al. 2009; Wu et al. 2011; Liu et al. 2012; Zhou and He 2015; Zhou et al. 2017). This phenomenon ultimately improves the self-purification capacity of freshwater ecosystem (Xu et al. 2014). Therefore, aquatic plants play important roles in contaminant removal, water purification, and maintenance of ecosystem functions in freshwater ecosystem (Wu et al. 2011; Liu et al. 2012; Zhou et al. 2017).

However, most aquatic macrophytes decay and die at the end of their life cycle. When the macrophytes die or undergo senescence, the decomposition process begins (Li et al. 2012), resulting in nutrients (N and P) and organic matter in the biomass to be eventually released into the water column, contributing a surplus of nutrients and other pollutants from their dead tissues to the freshwater system (Kuehn et al. 1999; Longhi et al. 2008; Liu et al. 2010; Lan et al. 2012) during the decay processes if not timely harvested (Kuehn et al. 1999; Longhi et al. 2008; Liu et al. 2010). More importantly, the decomposition of aquatic macrophytes may have further negative effects (Pereira et al. 1994; Xie et al. 2004), including reduced dissolved oxygen level in the water due to the rapid depletion and reduced underwater illumination intensity, which influence the redox processes (Longhi et al. 2008) and change the bacterial/fungal community and structure. The decomposition dynamics of aquatic macrophytes have important consequences in scientific management of aquatic macrophytes. Therefore, aquatic macrophytes need to be adequately managed to sustain the structure and functions of the freshwater ecosystem to avoid potential ecological consequences.

Nelumbo nucifera and *Trapa bispinosa* Roxb. are the two of most common and important aquatic plants in China's freshwater lake, especially in landscape lakes. These aquatic species are usually grown in the transitional areas between the shore and open water (Wu et al. 2007) and are rooted in the sediment and their petioles hold the leaves floating on the water surface (Wu et al. 2007; Seto et al. 2013; Zhou and He 2015; Xu et al. 2014). These two species initially grow in the spring and rapidly grow from late May to September (Xu et al. 2014). At the end of October, plants begin to die, and more than 40% of the total plant detritus fall into the water. Inevitably, the nutrients and other pollutants in their dead tissues will be eventually released into the water column in the following decay processes. Although harvesting strategies for *T. bispinosa* had been reported by Xu et al. (2014), studying its harvesting practical operability in the field of application is still lacking. Therefore, to date, the main objective is still to understand their decomposition dynamics to provide scientific data for species suitable management strategies. Moreover, previous studies reported that external influencing factors, including temperature, nutrient availability, hydroperiod, and pH, may regulate the decomposing activity, thereby affecting the decomposition rate of aquatic plant detritus (Coughlan and Mayer 1992; Alvarez and Guerrero 2000; Lee and Bukaveckas 2002; Gulis and Suberkropp 2003; Hobbie and Gough 2004; Rejmánková and Houdková 2006; Rejmánková and Sirová 2007; Breeuwer et al. 2008; Manning et al. 2008; Liu et al. 2010; Balasubramanian et al. 2012; Hildebrandt et al. 2012; Geraldes et al. 2012; Li et al. 2013; Song et al. 2013; Bottino et al. 2016; Zhang et al. 2017). Therefore, identical plants may have different decomposition dynamics under varying environment conditions. By contrast, decomposition rate may vary among different plant species in the same climate region. Therefore, research data from a specific region may not be applicable to other regions for aquatic plant management. However, the decomposition dynamics of *N. nucifera* and *T. bispinosa* detritus in the freshwater ecosystem under the subtropical climate conditions in the East region of China remains unknown. In addition, the detritus quality of different tissues for identical plants will show significant variation, which also affects the decomposition rates of plant detritus. However, information on the decomposition dynamics of different tissue detritus is still very limited.

Hence, the objective of this study to elucidated the decomposition dynamic of leaves and stems (including petioles) for two aquatic macrophytes *T. bispinosa* and *N. nucifera* detritus by using the litterbag technique in a shallow lake in the east region of China. Specifically, our goals are (1) to examine the dynamics changes of detritus, decomposition rate, and the differences in species- and tissue-specific; (2) to study the dynamics change in C and nutrient concentration in plant detritus and nutrient accumulation/release; and (3) provide fundamental data for the management of aquatic plant in the freshwater ecosystems in the East region of China.

Materials and methods

Collection and preparation of two aquatic plant detritus

Fresh plant aboveground tissues of two aquatic macrophytes *N. nucifera* and *T. bispinosa* Roxb. were collected from the pond, which are located at Jiangsu University (32° 12′ 9″ N, 119° 30′ 53″ E) on September 2016. Then, the fresh samples were cleaned using tap water to remove any impurity adhering in the plant surface. Subsequently, the aboveground tissues were separated into leaves and stems (plus petioles) and then dried at 65 °C for 7 days to constant weight. Afterward, the dry plant material samples were cut into approximately 5–10-cm sections, and each section was thoroughly mixed to give a homogenous starting material before using in the following experiment.

Field decomposition experiment design

The field decomposition experiment was conducted using the litterbag technique. Oven-dried detritus of each plant tissues was placed inside 20 cm × 15 cm nylon litterbags with 0.5 mm mesh size; afterward, the bags were sealed. Each litterbag contains 10 g dried detritus. Then, these litterbags with identical plant tissues were all fixed using nylon ribbon into individual square cages to avoid the litterbags to escape and become intertwined. Then, four square cages with litterbags were submerged under water of approximately 0.5 m depth (out of touch with sediment) and incubated in identical pond with the collected plant detritus.

Triplicate litterbags of each tissue for the two species were randomly selected and retrieved from December 2016 to May 2017 and 9 times at 6, 14, 28, 45, 65, 90, 125, 145, and 165 days after the decomposition experiment. For each collection, litterbags were immediately brought back to the laboratory and were washed thoroughly with tap water to remove any adhered impurity. Afterward, the plant detritus was removed thoroughly from litterbags and oven dried at 65 °C for 10 days until the constant weight to measure the dry mass remaining. Then, the plant detritus was powdered prior to chemical analyses.

Plant detritus chemistry analysis

Samples of the initial detritus and collected from the litterbags were analyzed for the C, N, and P contents. The total N (TN) in detritus was analyzed using the Nessler reagent colorimetric method (digested by H_2SO_4+H_2O_2), while the total P (TP) concentration was analyzed using the molybdenum antimony anticolorimetric method (digested by H_2SO_4+H_2O_2). The total C concentration in plant detritus was determined using the TOC analyzer (TOC-L CPN 638-91110-43, Shimadzu).

Data calculation

1. Decomposition rate constants (k) of detritus dry mass were calculated and modeled by first-order models (Olson 1963) using Eq. (1). Simultaneously, the time required to decompose 50% ($t_{50\%}$) and 95% ($t_{95\%}$) dry mass and the turnover rates (1/k) were calculated according to method previously reported in the literature (Singh and Shekhar 1989; Balasubramanian et al. 2012):

$$W_t = W_0 e^{-kt} \quad (1)$$

where t is the time in days, W_t (g) is the dry mass remaining of each plant detritus at time t, W_0 (g) is the initial dry weight of each plant detritus (10 g) at time 0, and e is the base of the natural logarithm.

2. The accumulation index (AI, %) and release index (RI, %) of C, N, and P were calculated using Eqs. (2) and (3) according to method previously reported in the literature (Chimney and Pietro 2006; Xie et al. 2004; Romero et al. 2005). AI was used to express the net accumulation status during detritus decomposition. AI value of greater than 100% indicated net accumulation, while AI value of less than 100% indicated net release (Deng et al. 2016). The RI values were varied in the reverse way compared with AI.

$$AI = \frac{W_t \times N_t}{W_0 \times N_0} \times 100 \quad (2)$$

$$RI = \left(1 - \frac{W_t \times N_t}{W_0 \times N_0}\right) \times 100 \quad (3)$$

where t is the time (days), W_t (g) is the detritus dry mass remaining at time t, W_0 (g) is the detritus initial dry weight (10 g) at time 0, N_t (g/kg) is the concentration of C, N, and P in the detritus remaining at time t, and N_0 (g/kg) is the initial concentration of C, N, and P at time 0.

Statistical analyses

All the data were calculated and statistically analyzed using Microsoft Excel, and the results were presented as means ± SD. Two-way ANOVA was conducted to compare the dry mass remaining/loss; content of C, N, and P; and AI of C, N, and P with species and decomposition time as the main effects. The relationships between decomposition rate and plant nutrient content was studied using Pearson correlation analysis, with significant levels at $P < 0.05$ or 0.01 for all the analyses.

Results

Dynamics changes in the detritus dry matter

The dynamics change curve of the dry mass remaining for stems (plus petiole) and leaves detritus of *N. nucifera* and *T. bispinosa* with decomposition time are shown in Fig. 1. For *N. nucifera*, 19.20, 19.95, 27.75, 29.35, and 40.55% of the initial dry mass were decomposed from the stems (plus petiole) detritus on days 6, 14, 28, 45, and 65, respectively. During the same times, 17.75, 20.55, 27.00, 35.90, and 40.45% of the initial dry mass were respectively decomposed from the leaves detritus. The dry mass loss rate of stems (plus petiole) and leaves detritus had no significant difference in this decomposition stage (days 0–65) ($P > 0.1$). During the later decomposition period (days 65–165), the ratio of the dry mass loss to the initial values from 32.95 to 49.35% for stems (plus petiole) detritus and 45.40–69.40% dry mass loss from leaves

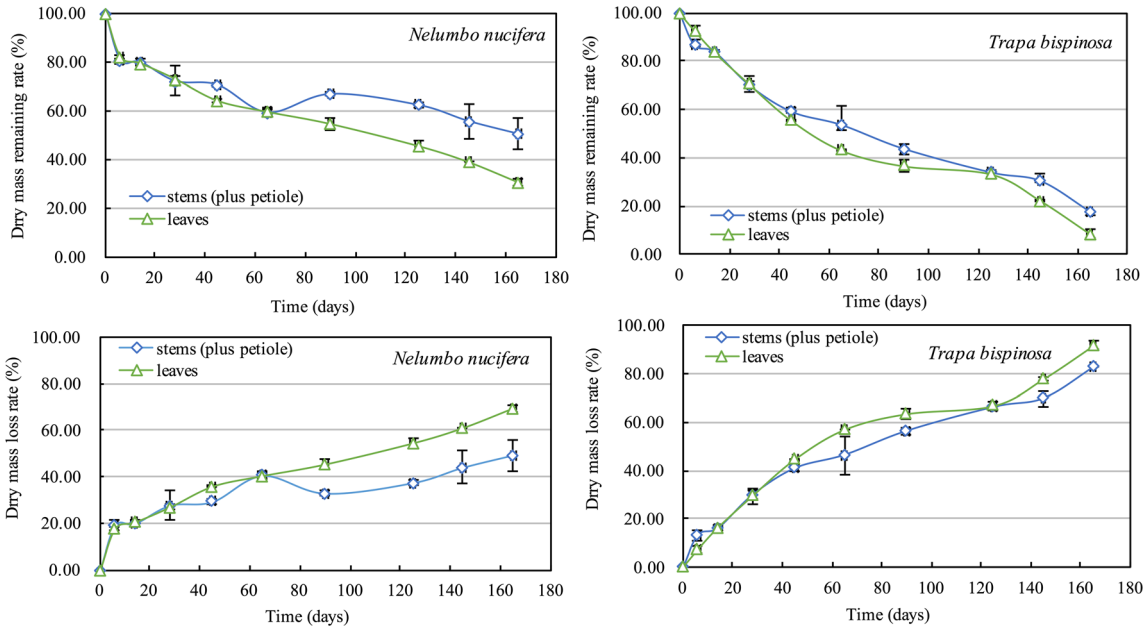

Fig. 1 Dry mass remaining/loss rate of two aquatic macrophytes detritus during the 165-day decaying period

detritus, indicating faster dry mass loss in the leaves detritus than stems (plus petiole) detritus. A significant difference in the mass loss was found between stems (plus petiole) and leaves in the following decomposition stage (days 65–165) ($P < 0.05$). At the end of the decomposition experiment (day 165), the ratios of dry mass remaining to the initial mass were 50.65 and 30.60% for the stems (plus petiole) and leaves detritus of *N. nucifera*, respectively. This result indicated that approximately half of the stems (plus petiole) detritus and more than 60% of the leaves detritus can be decomposed for *N. nucifera* after decomposing for 165 days. For *T. bispinosa,* the dry mass of stems (plus petiole) and leaves detritus were both obviously decreased with decomposition time and loss rate reached 82.65% for stems (plus petiole) and 91.65% for leaves after decomposition 165 days, respectively, indicated that over more than 80% of the dry mattes could be decomposed after 165 days. In addition, no significant differences were found between the stems (plus petiole) and leaves of *T. bispinosa* detritus dry mass during the whole decomposition processing ($P > 0.1$). Furthermore, dry mass loss rate was 1.67-fold for stems (plus petiole) detritus and 1.32-fold for leaves detritus of *T. bispinosa* compared with that of values of *N. nucifera* at the end of decomposition experiment, indicating that the dry mass of *T. bispinosa* detritus were decomposed faster than the *N. nucifera* detritus. These results suggested that species interspecific had significant influences on detritus decomposition.

Furthermore, two-way ANOVA results showed that species, decomposition time, and their interaction all had significant effects on detritus dry mass loss ($P < 0.0001$) (Table 1). Moreover, a higher F value for decomposition time ($F = 625.90$) than that for species ($F = 128.84$) was observed,

Table 1 Two-way ANOVA analysis (plant species × decaying time) for dry matter loss, chemical properties (C, N, P, C/N, C/P, N/P), and their interactions

Source of variation		Dry matter remains	C	N	P	C/N	C/P	N/P	*AI*[a] of C	*AI*[a] of N	*AI*[a] of P
Species	*df*	3	3	3	3	3	3	3	3	3	3
	F values	128.84	161.16	0.67	41.93	25.13	174.44	85.06	203.79	13.19	6.45
	P value	< 0.0001	< 0.0001	0.57	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	0.0012
Time	*df*	9	9	9	9	9	9	9	9	9	9
	F values	625.90	591.40	30.88	13.45	67.20	54.75	4.67	411.77	56.54	32.22
	P value	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	0.0003	< 0.0001	< 0.0001	< 0.0001
Species× times	*df*	27	27	27	27	27	27	27	27	27	27
	F values	19.41	102.62	3.32	1.43	14.25	17.94	2.44	38.31	1.83	0.83
	P value	< 0.0001	< 0.0001	0.0003	0.1494	< 0.0001	< 0.0001	0.005	< 0.0001	0.04	0.69

[a] Accumulation index (*AI*) and its value was calculated according to the Eq. (2)

which indicates that the decomposition time had a more specific effect on detritus decomposition than species interspecific effects (Table 1).

In addition, the relationship between the detritus mass losses at different decomposition times and initial detritus quality parameters were analyzed according to Pearson correlation analysis (Table 2). The results showed that mass losses during the initial stage (day 6) were positively correlated with detritus C/P and N/P ratios ($P < 0.05$) and negatively correlated with initial the P concentration ($P < 0.01$). However, those relationships were significantly changed with increasing decomposition time. Mass losses were negatively correlated with N/P (days 45 and 90–165) ($P < 0.01$) and C/P ratios (days 45, 90, and 145–165) and positively correlated with the initial P concentration (days 45–165) ($P < 0.05$). These results indicated that the initial chemistry of detritus, particularly P-related parameters (P concentration and C/P and N/P ratios), strongly affected the detritus dry mass loss, and these effects were also changed with decomposition time.

k value

The *k* value ranged from 0.0030 to 0.0122 day^{-1} (Table 3). The highest *k* value was obtained in the leaves detritus of species *T. bispinosa,* followed by its stems (plus petiole), while the lowest value was found in the stems (plus petiole) detritus of species *N. nucifera*. In addition, lower *k* values were observed in the stems (plus petiole) detritus compared with that in leaves for identical species. Furthermore, lower *k* values were observed for *N. nucifera* compared with identical tissues for *T. bispinosa*. According to Pearson correlation analysis (Table 4), the *k* values were positively correlated with the initial P concentration ($P < 0.01$) and negatively correlated with the C/P ($P < 0.05$) and N/P ratios of detritus ($P < 0.01$). These results indicated that the initial chemistry parameters can strong affect the detritus decomposition rates.

The time for 50% ($t_{50\%}$) dry mass decomposition on the basis of the *k* values ranged from 115.92 to 230.75 days for *N. nucifera*. Meanwhile, $t_{50\%}$ ranged from 57.17 to 76.94 days for *T. bispinosa* (Table 3), and its order is as follows: leaves < stems (plus petiole) for identical species, and *T. bispinosa* < *N. nucifera*. The $t_{95\%}$ and turnover rate show similar orders with $t_{50\%}$. These results indicated that the stems (plus petiole) need longer time to decay 50 or 95% dry mass compared with leaves. In addition, *N. nucifera* needs longer time for 50 and 95% of dry mass loss compared with *T. bispinosa*.

Dynamics changes of C and nutrient concentration in plant detritus

The initial C and nutrient characteristics of two aquatic macrophyte detritus used in this study are shown in Table 5. For *N. nucifera*, the C, N, and P concentration of the stems (plus petiole) were lower than that of the leaves detritus, whereas the C/N, C/P, and N/P ratios in stems (plus petiole) were all higher than those in the leaves detritus. For *T. bispinosa,* higher values of C content and C/N, C/P, and N/P the ratios were obtained in the stems (plus petiole) than that in leaves detritus.

Dynamics changes in the C, N, and P concentration during the whole decomposition time are shown in Fig. 2. C concentration in leaves and stems of both species strongly fluctuated over the whole decomposition time (Fig. 2). The maximum value of C concentration reached 753.00, 850.50, 728.50, and 904.50 g/kg, in stems (plus petiole) of *N. nucifera*, leaves of *N. nucifera*, stems (plus petiole) of *T. bispinosa*, and leaves of *T. bispinosa*, respectively, which were 1.75-, 1.43-, 1.00-, and 1.99-fold higher compared with their initial values in the same tissues (Tables 5 and 6). At the end of the experiment, C contents of 49.42, 55.41, 42.42, and 74.48% were remained compared with their initial C content in the stems (plus petiole) of *N. nucifera*, leaves of *N. nucifera*, stems (plus petiole)

Table 2 Relationship between the detritus mass losses at different decomposition time and initial detritus quality parameter during the decomposition experiment processing

Detritus mass losses	Initial detritus quality parameter					
	C	N	P	C/N	C/P	N/P
Day 6	0.0339	0.1333	− 0.9518*	− 0.0422	0.9147*	0.8885*
Day 14	− 0.3004	0.5308	− 0.8450	− 0.5549	0.6287	0.8861*
Day 28	0.3019	− 0.6463	0.7576	0.6320	− 0.5100	− 0.8141
Day 45	0.3004	0.0293	0.9978**	0.1913	− 0.9342*	− 0.9844**
Day 65	− 0.1809	− 0.1774	0.8929*	− 0.0402	− 0.8753	− 0.8083
Day 90	0.3035	0.0003	0.9982**	0.2123	− 0.9259*	− 0.9876**
day 125	0.5141	0.0499	0.9560*	0.3416	− 0.8531	− 0.9860**
Day 145	0.3257	0.1050	0.9903**	0.1619	− 0.9422*	− 0.9765**
Day 165	0.3395	0.0587	0.9931**	0.2022	− 0.9293*	− 0.9854**

*$p < 0.05$; **$p < 0.01$

Table 3 Decomposition rates constants (k) and turnover rate of aquatic plants detritus obtained from the first-order linear model fit of $\log_e(W_t)$ to t (values = mean ± SD)

Species		k (day^{-1})	R^2	$t_{50\%}$ (days)	$t_{95\%}$ (days)	Turnover rate (days)
Nelumbo nucifera	Stems (plus petiole)	0.0030 ± 0.0001	0.766 ± 0.023	230.75 ± 5.97	997.25 ± 25.81	332.89 ± 8.62
	Leaves	0.0060 ± 0.0003	0.967 ± 0.009	115.92 ± 5.07	501.02 ± 21.90	167.24 ± 7.31
Trapa bispinosa	Stems (plus petiole)	0.0090 ± 0.0003	0.960 ± 0.016	76.94 ± 2.84	332.53 ± 12.26	111.00 ± 4.09
	Leaves	0.0122 ± 0.0009	0.908 ± 0.014	57.17 ± 4.09	247.09 ± 17.68	82.48 ± 5.90

of *T. bispinosa*, and leaves of *T. bispinosa*, respectively. In addition, no significant difference in the C concentration was obtained in both species ($P > 0.05$). Moreover, both the leaves and stems (plus petiole) for the same species were not significantly different ($P > 0.05$). Two-way factorial ANOVA indicated that the C concentration in plant detritus was significantly different between plant species and decomposition time ($P < 0.01$) (Table 1).

The N concentration was rapidly decreased by 72.70, 77.58, 61.08, and 71.02% compared with their initial values in the stems (plus petiole) of *N. nucifera*, leaves of *N. nucifera*, stems (plus petiole) of *T. bispinosa*, and leaves of *T. bispinosa*, respectively, in the initial decomposition stage (day 6). Then, the N concentration fluctuated from 5.39 to 16.88, 6.45 to 13.48, 6.90 to 16.54, and 6.73 to 16.21 g/kg in the following decomposition time (Fig. 2) in the stems (plus petiole) of *N. nucifera*, leaves of *N. nucifera*, stems (plus petiole) of *T. bispinosa*, and leaves of *T. bispinosa*, respectively. At the end of the experiment, 63.74, 26.17, 36.56, and 28.51% of N remained compared with their initial values in the stems (plus petiole) of *N. nucifera*, leaves of *N. nucifera*, stems (plus petiole) of *T. bispinosa*, and leaves of *T. bispinosa*, respectively. No significant difference in the N concentration was obtained in the stems (plus petiole) and leaves of *N. nucifera* and *T. bispinosa* ($P > 0.05$). The variation in N concentration in plant detritus was significantly different among the sampling days ($P < 0.01$) and interactions between the species and decomposition time ($P < 0.01$), whereas it was not significantly different between plant species ($P > 0.05$) (Table 1).

The P concentration fluctuated gradually from 0.50 to 1.90, 1.18 to 3.70, 1.02 to 5.34, and 1.30 to 6.71 g/kg in the stems (plus petiole) of *N. nucifera*, leaves of *N. nucifera*, stems (plus petiole) of *T. bispinosa*, and leaves of *T. bispinosa*, respectively, throughout the whole decomposition process (Fig. 2). At the end of the experiment, 58.73, 31.76, 19.11, and 19.34% of P remained compared with their initial values in the stems (plus petiole) of *N. nucifera*, leaves of *N. nucifera*, stems (plus petiole) of *T. bispinosa*, and leaves of *T. bispinosa*, respectively. Significant differences in P concentration were found between the stems (plus petiole) and leaves of *N. nucifera* ($P < 0.01$) and between *N. nucifera* and *T. bispinosa* ($P < 0.01$). Meanwhile, no significant difference in the P concentration was observed in the stems (plus petiole) and leaves of *T. bispinosa* ($P > 0.05$). Two-way factorial ANOVA elucidated that the P concentration in plant detritus was significantly different within the plant species ($P < 0.01$) and decomposition time ($P < 0.01$), whereas no significant difference was found for the interactions between the plant species and decomposition time ($P > 0.05$) (Table 1).

In addition, the C/N, C/P, and N/P ratios of plant detritus also resented the irregular and different temporal change trends during the whole decomposition process (Fig. 3, Table 5). Two-way ANOVA results suggested that the C/N, C/P, and N/P ratios were significantly different among the plant species ($P < 0.01$), decaying days ($P < 0.01$), and their interactions ($P < 0.01$) (Table 1). Furthermore, species had a more significant effect on the C/P and N/P ratios than decomposition time, whereas the decomposition time had a more significant effect on C/N ratio than species on the basis of their F values from the two-way ANOVA results (Table 1).

Table 4 Pearson's correlation coefficients (r) of decomposition rate and chemical components in plants litters

r	k	C	N	P	C/N	C/P	N/P
k	1.000						
C	0.178	1.000					
N	− 0.021	− 0.012	1.000				
P	0.997**	0.246	− 0.004	1.000			
C/N	0.130	0.765	− 0.653	0.171	1.000		
C/P	− 0.946*	− 0.029	− 0.273	− 0.939*	0.171	1.000	
N/P	− 0.964**	− 0.427	0.084	− 0.978**	− 0.361	0.857	1.000

* and ** indicate significant level at $P < 0.05$ and 0.01 level, respectively

AI/RI of C and nutrient in plant detritus

AI of C and nutrient in the plant detritus were calculated, and their dynamics change curves during the whole decomposition process are shown in Fig. 4. The *AI* of N in two plant detritus was sharply decreased by 76.41, 81.58, 66.22, and 72.43% in the stems (plus petiole) of *N. nucifera*, leaves of

Table 5 Initial C and nutrient characteristics of two aquatic macrophytes detritus using in this study

Chemistry parameter	*Nelumbo nucifera*		*Trapa bispinosa*	
	Stems (plus petiole)	Leaves	Stems (plus petiole)	Leaves
C (g/kg)	431.00 ± 55.15	596.50 ± 9.19	728.50 ± 10.61	454.50 ± 26.16
N (g/kg)	19.74 ± 7.59	31.25 ± 2.55	18.86 ± 1.23	23.60 ± 4.60
P (g/kg)	1.90 ± 0.66	3.70 ± 0.43	5.34 ± 3.13	6.71 ± 1.86
C/N	23.00 ± 6.05	19.16 ± 1.86	38.73 ± 3.09	19.74 ± 4.95
C/P	246.57 ± 114.22	162.45 ± 21.30	164.07 ± 94.25	69.88 ± 15.46
N/P	11.78 ± 8.07	8.46 ± 0.29	4.35 ± 2.78	3.76 ± 1.73

N. nucifera, stems (plus petiole) of *T. bispinosa*, and leaves of *T. bispinosa*, respectively, on the first 6 days. Then, the *AI* of N fluctuated from 23.59 to 50.84, 8.08 to 27.51, 6.35 to 55.88, and from 2.56 to 49.12% in the stems (plus petiole) of *N. nucifera*, leaves of *N. nucifera*, stems (plus petiole) of *T. bispinosa*, and leaves of *T. bispinosa*, respectively, during the following days (days 6–165). Similar changes have been found for *AI* of P in plant detritus. At the end of the decomposition experiment, the *AI* values of N and P were 36.72 and 31.25% in the stems (plus petiole) of *N. nucifera*, 8.08 and 9.85% in leaves of *N. nucifera*, 6.35 and 4.00% in stems (plus petiole) of *T. bispinosa*, 2.56 and 1.63% in leaves of *T. bispinosa*, respectively. These results indicated that 63.28 and 68.75% in the stems of *N. nucifera*, 91.92 and 90.15% in the leaves of *N. nucifera*, 93.65 and 96.00% in the stems (plus petiole) of *T. bispinosa*, 97.44 and 98.37% in the leaves of *T. bispinosa* of N and P, respectively, were transferred from the plant detritus to the water compared with their initial values.

For C, the *AI* value was higher than 100% in the stems (plus petiole) and leaves detritus on day 14 and in the stems (plus petiole) detritus on day 90 for *N. nucifera*. For *T. bispinosa*, the *AI* value was lower than 100% during

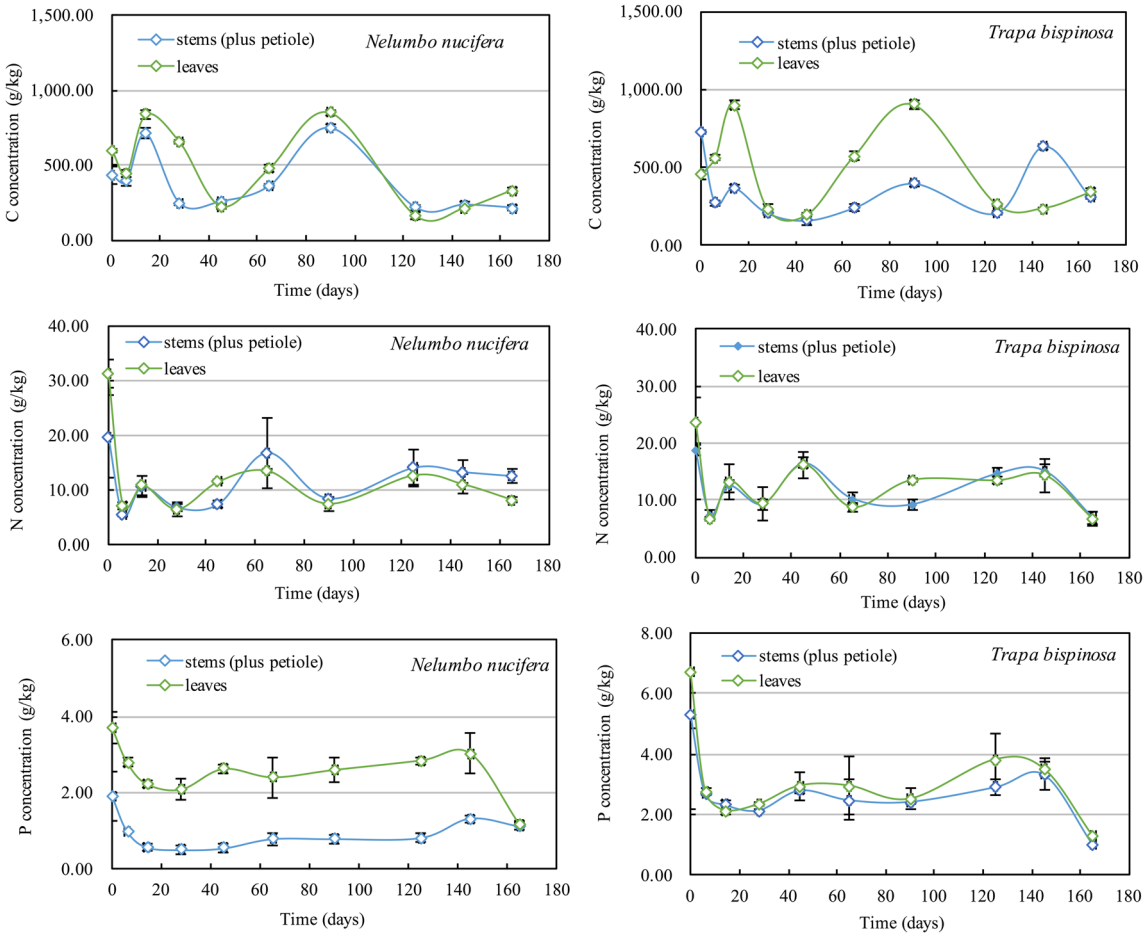

Fig. 2 Dynamic changes of C, N, and P content of two aquatic macrophytes detritus during the 165-day decaying period

Table 6 Change of C and nutrient characteristics of two aquatic macrophytes detritus

Chemistry parameter		*Nelumbo nucifera*		*Trapa bispinosa*	
		Stems (plus petiole)	Leaves	Stems (plus petiole)	Leaves
C	Mean value (g/kg)	380.40	477.80	353.75	465.65
	Minimum value (g/kg)	213.00	159.50	162.50	193.50
	Maximum value (g/kg)	753.00	850.50	728.50	904.50
	SD	201.86	252.77	188.77	267.20
	CV (%)	53.07	52.90	53.36	57.38
N	Mean value (g/kg)	11.54	11.99	12.06	12.60
	Minimum value (g/kg)	5.39	6.45	6.90	6.73
	Maximum value (g/kg)	19.74	31.25	18.86	23.60
	SD	4.65	7.20	4.10	5.08
	CV (%)	40.26	60.06	34.02	40.31
P	Mean value (g/kg)	0.93	2.55	2.75	3.11
	Minimum value (g/kg)	0.50	1.18	1.02	1.30
	Maximum value (g/kg)	1.90	3.70	5.34	6.71
	SD	0.43	0.66	1.09	1.45
	CV (%)	45.96	25.96	39.77	46.68
C/N	Mean value	39.65	50.64	30.68	43.09
	Minimum value	15.76	12.79	9.93	12.12
	Maximum value	89.05	116.17	44.80	82.24
	SD	26.95	37.44	12.46	26.74
	CV (%)	67.96	73.94	40.60	62.05
C/P	Mean value	495.20	203.87	141.36	182.59
	Minimum value	175.95	56.29	57.99	65.90
	Maximum value	1265.59	376.19	302.85	421.89
	SD	356.06	116.09	72.09	131.71
	CV (%)	71.90	56.94	51.00	72.14
N/P	Mean value	13.51	4.70	4.72	4.33
	Minimum value	5.43	2.51	2.73	2.46
	Maximum value	21.09	8.46	6.76	6.27
	SD	4.66	1.89	1.13	1.22
	CV (%)	34.49	40.20	23.94	28.17

SD standard deviation, *CV* coefficients of variation

the whole decomposition experiment in stems detritus. Meanwhile, the *AI* values were 114.72 and 166.19% in the leaves detritus on days 6 and 14 and then decreased from 72.83 to 6.16% from day 28 to day 165 (Fig. 4). At the end of the incubation period, 25.15, 16.96, 7.36, and 6.16% of the *AI* values were found in detritus, indicating that the C contents of 74.85% in the stems (plus petiole) of *N. nucifera*, 83.04% in the leaves of *N. nucifera*, 92.64% in stems (plus petiole) of *T. bispinosa*, 93.84% in leaves of *T. bispinosa* compared with their initial value were transferred and released from the plant detritus to the water.

In addition, no significant difference on the C, N, and P *AI* values was observed between *N. nucifera* and *T. bispinosa* ($P > 0.05$) and between the leaves and stems (plus petiole) of the same species ($P > 0.05$). Two-way factorial ANOVA indicated that the C, N, and P *AI* values in the plant detritus were significantly affected by plant species and decomposition time ($P < 0.01$) (Table 1). The interactions between the species and decomposition time significantly affected the C and N *AI* values ($P < 0.05$); however, this interaction did not significantly affect the P *AI* values in the detritus ($P > 0.1$) (Table 1). Furthermore, the decomposition time had a more significant effect on the AI value of C, N. and P than species on the basis of their *F* values from the results of two-way ANOVA (Table 1).

In addition, *RI* values of C, N and P were correlated with the initial detritus quality parameter, according to Pearson correlation analysis (Tables 7, 8, and 9) at the different decomposition times. Moreover, these relationships were also significantly changed with the decomposition time. These results indicated that the initial chemistry properties of detritus, to a certain extent, affected the C and nutrient accumulation/release from detritus into the water.

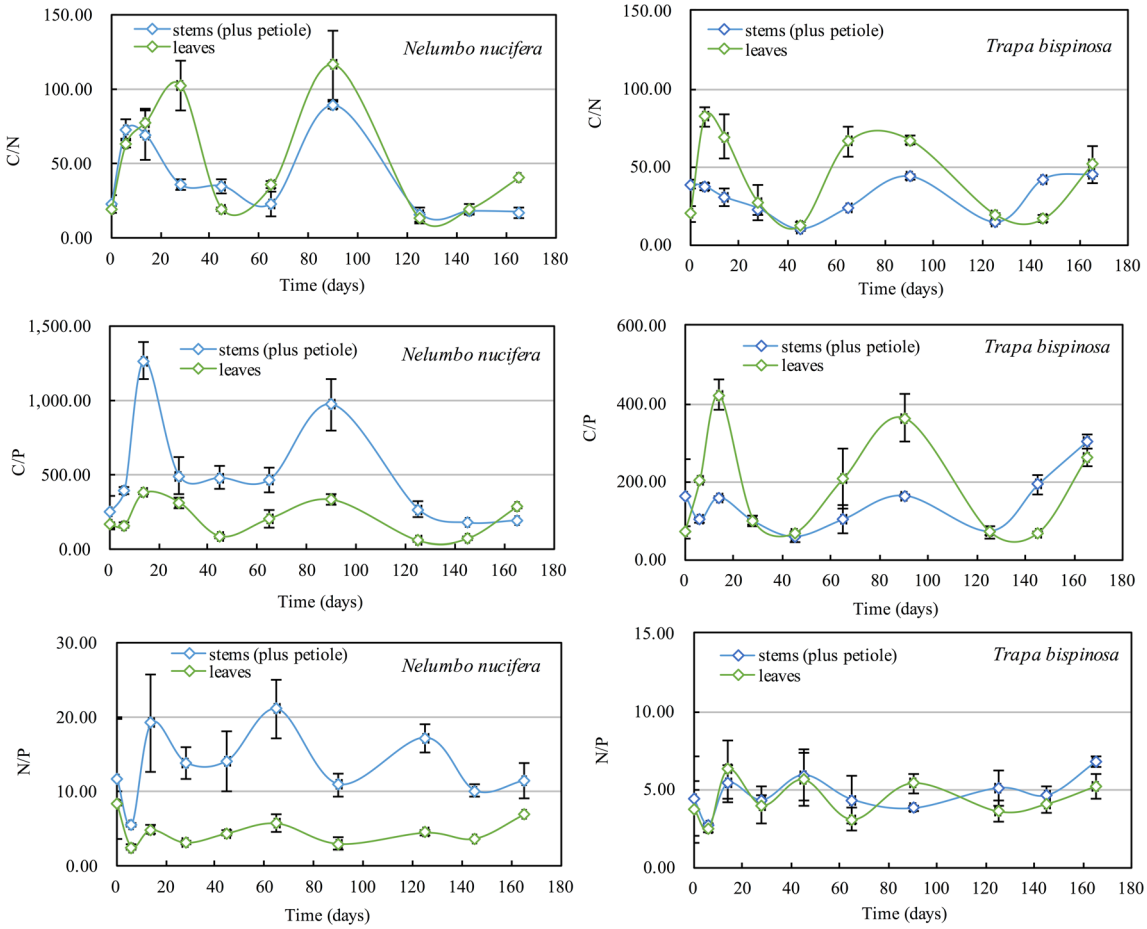

Fig. 3 Changes of C/N, C/P, and N/P ratio of of two aquatic macrophytes detritus during the 165-day decaying period

Discussion

Detritus dry mass loss, decomposition rate, and their influencing factors

In our study, higher dry detritus loss of *T. bispinosa* (mean loss rate 87.15%) were found than the dry detritus loss of *N. nucifera* (mean loss rate 59.38%), indicating that the *T. bispinosa* detritus is decomposed faster than *N. nucifera* detritus after decomposition for 165 days. Furthermore, the *k* values obtained from the first-order linear model also verified that the decomposition rate were significantly higher for *T. bispinosa* ($k = 0.0106$) than *N. nucifera* ($k = 0.0045$). These results indicated the detritus decomposition of these two aquatic macrophytes were highly species–specific. Similar results were reported by previous studies (Xie et al. 2004; Li et al. 2013). Li et al. (2013), for example, reported that no more than 26% mass remains compared with the initial detritus mass remaining for *Ceratophyllum demersum* L., with the fastest decomposition rate, whereas, more than 55% mass remains compared with the initial detritus mass remaining for *Phragmites australis* with the lowest decomposition rate. Chimney and Pietro (2006) also reported that the highest decomposition rates are observed in *Najas/Ceratophyllum*, followed by *Pistia*, *Eichhornia*, submerged *Typha*, and the lowest values were obtained in aerial *Typha*.

In addition, the decomposition of *N. nucifera and T. bispinosa* were highly tissue-specific. In this study, lower *k* values were observed in stems (plus petiole) detritus compared with that the *k* values in leaves detritus for identical species. After decomposition for 165 days, higher dry mass losses (69.40 and 91.65%) were obtained for the leaves of *N. nucifera and T. bispinosa* than their stems (plus petiole) (49.35 and 82.65%). Moreover, the detritus mass losses of leaves for these two macrophytes were higher than 60%. Meanwhile, the mass loss was approximately 50% for *N. nucifera* stems (plus petiole). Similar results were found by the study of Lan et al. (2012), who reported that the order of decomposition rate is leaves > stems > roots for *Nelumbo nucifera* and *Potamogeton pectinatus*. Li et al. (2012) also found that the mean decomposition rates of *N. nucifera* are the highest in the leaves tissues (0.0061 day^{-1}), and the mean decomposition rates in the leaves tissues were consistent with those in stem and root tissues (0.0044 day^{-1}). Bedford (2005) also reported than approximately 15% dry weight are lost from

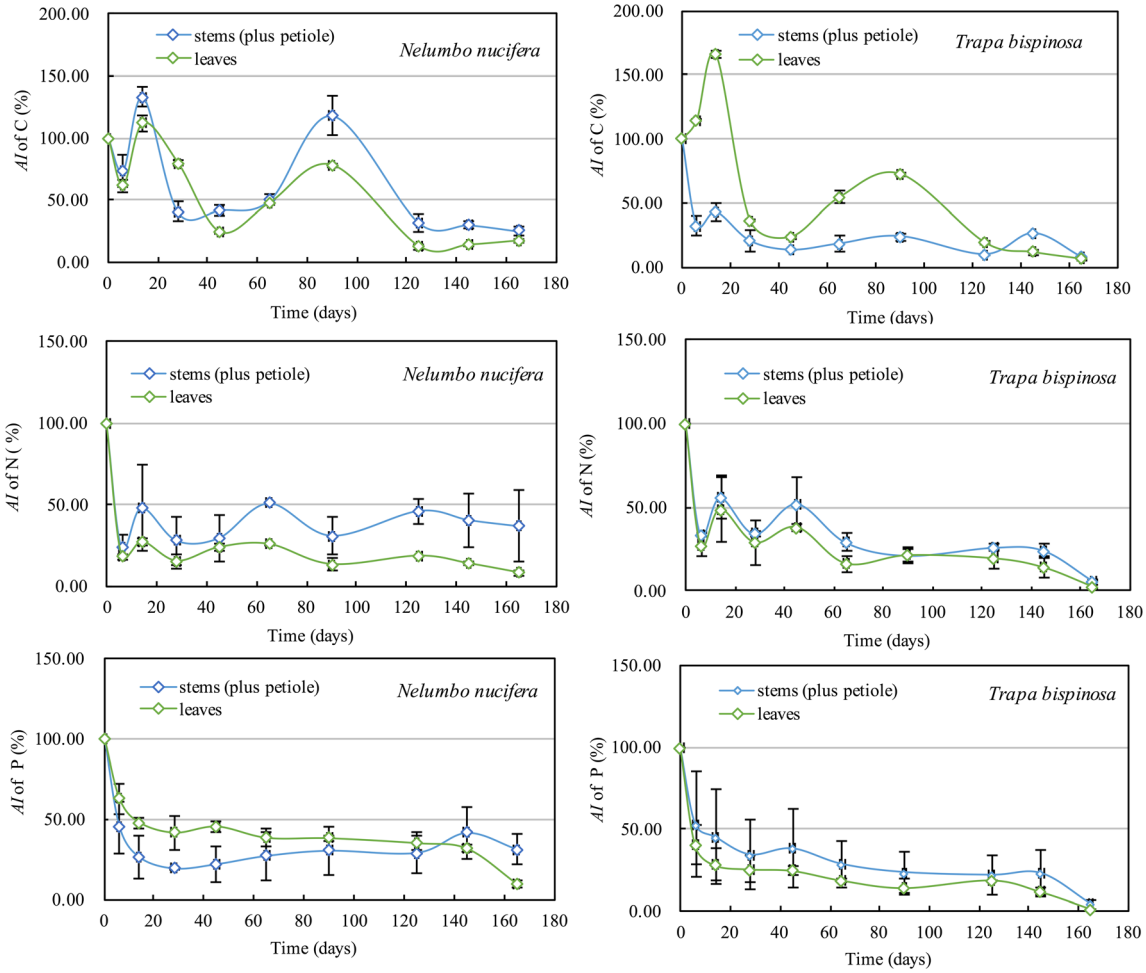

Fig. 4 *AI* values of two aquatic macrophytes detritus during the 165-day decaying period

P. australis leaves, whereas only 5% mass loss is observed from the stems compared with the initial mass after 65 days.

The difference in detritus dry mass loss and their decomposition rate may be affected by the initial detritus quality. Detritus quality is defined as the chemical characteristics of decomposition substrate (Li et al. 2013), and its parameters include C, N, P concentrations and C/N, C/P, N/P, and lignin/N ratios (Chimney and Pietro 2006; Berg and McClaugherty 2008; Liao et al. 2008). Countless studies have confirmed that the initial detritus quality is an important index to determine

Table 7 Relationship between the C release index of detritus at different decomposition time and initial detritus quality parameter during the decomposition experiment processing

Release index of C	Initial detritus quality parameter					
	C	N	P	C/N	C/P	N/P
Day 6	0.8371	−0.1672	−0.3017	0.7509	0.5226	0.1026
Day 14	0.9286*	−0.2776	−0.0217	0.8864*	0.2945	−0.1843
Day 28	0.1412	−0.9350*	0.3559	0.7030	−0.0663	−0.4316
Day 45	0.8177	0.0901	0.7506	0.5507	−0.5960	−0.8516
Day 65	0.8987*	−0.4466	0.1727	0.9688**	0.1418	−0.3723
Day 90	0.8685	−0.1462	0.6760	0.7430	−0.4464	−0.8108
Day 125	0.8536	0.3449	0.5788	0.4172	−0.4880	−0.6791
Day 145	−0.1121	0.7499	0.6049	−0.5796	−0.8298	−0.4817
Day 165	0.4391	−0.0730	0.9765**	0.3631	−0.8555	−0.9998**

*$p < 0.05$; **$p < 0.01$

Table 8 Relationship between the N release index of detritus at different decomposition time and initial detritus quality parameter during the decomposition experiment processing

Release index of N	Initial detritus quality parameter					
	C	N	P	C/N	C/P	N/P
Day 6	− 0.4373	0.7800	− 0.5512	− 0.8251	0.2398	0.6593
Day 14	− 0.0729	0.9491*	− 0.3184	− 0.6608	0.0397	0.3844
Day 28	− 0.1432	0.9354*	− 0.3543	− 0.7049	0.0641	0.4305
Day 45	− 0.5624	0.6920	− 0.5878	− 0.8630	0.2738	0.7111
Day 65	0.2549	0.4402	0.8951*	− 0.1061	− 0.9548*	− 0.8479
Day 90	0.5054	0.8077	0.4012	− 0.1428	− 0.5127	− 0.4093
Day 125	0.3954	0.6199	0.7491	− 0.1121	− 0.8296	− 0.7258
Day 145	0.2718	0.6817	0.7212	− 0.2455	− 0.8450	− 0.6707
Day 165	0.4988	0.3658	0.8811*	0.1278	− 0.8688*	− 0.8887*

*$p < 0.05$; **$p < 0.01$

the detritus decomposition dynamics (Melillo et al. 1982; Berg et al. 2000; Rogers and Campbell 2004; Chimney and Pietro 2006; Li et al. 2013; Zhu et al. 2013). Lan et al. (2012) reported the remaining biomass is significantly affected by the N concentration and the C/N and N/P ratios; moreover, a lower decomposition rate are found in the stems and roots due to higher C/N ratio, lower N/P ratio, and lower N concentration in these tissues. Li et al. (2013) also confirmed that the high initial N and P concentration and low initial C/N, C/P, and N/P ratios in plant detritus are usually associated with high decomposition rate. Chimney and Pietro (2006) found negative correlations between decomposition rates and C/N and C/P ratios. Additionally, initial detritus quality has been widely recognized as one of the dominant factors in determining the variation of decomposition rates for various aquatic plants. In this study, the decomposition dynamics of *T. bispinosa* and *N. nucifera* were affected by the initial detritus quality. These effects can be summarized in two points. First, detritus mass losses were affected by the initial detritus quality. Our results showed that mass losses of *T. bispinosa* and *N. nucifera* were positively correlated with detritus C/P and N/P ratios ($P < 0.05$) and negatively correlated with the initial P concentration ($P < 0.01$) during the initial stage (day 6). However, these relationships were significantly changed with increasing decomposition time. Mass losses were negatively correlated with N/P (days 45 and 90–165) ($P < 0.01$) and C/P ratios (days 45, 90, and 145–165) and positively correlated with the initial P concentration (days 45–165) ($P < 0.05$). Our research results indicated that the initial detritus chemistry, particularly the P-related parameters (P concentration and C/P and N/P ratio), strongly affected the detritus dry mass loss, and these effects were also changed with decomposition time. Moreover, the initial C and N concentrations and C/N ratio had slight influence on *T. bispinosa* and *N. nucifera* detritus mass loss. This result is consistent with the findings of the previous report (Li et al. 2012a), indicating that the relationship between mean mass loss and initial litter quality factors, such as P concentration and C/P ratio. Therefore, P-related indicators of detritus are the best indicator for mass loss (Li et al. 2012, 2013). Second, *k* values were affected by the initial detritus quality. In our research, the *k* values were positively correlated with initial P contents ($P < 0.01$) and

Table 9 Relationship between the P release index of detritus at different decomposition time and initial detritus quality parameter during the decomposition experiment processing

Release index of P	Initial detritus quality parameter					
	C	N	P	C/N	C/P	N/P
Days 6	− 0.6512	− 0.6109	0.2662	− 0.1075	− 0.2342	− 0.1670
Days 14	− 0.8769	− 0.4521	− 0.0898	− 0.3750	0.0275	0.2208
Days 28	− 0.7379	− 0.6653	− 0.2090	− 0.1296	0.2338	0.2876
Days 45	− 0.7786	− 0.6049	− 0.0668	− 0.2021	0.0675	0.1681
Days 65	− 0.4647	− 0.5964	0.5157	0.0206	− 0.4462	− 0.4345
Days 90	− 0.1685	− 0.5197	0.7697	0.1920	− 0.6565	− 0.7229
days 125	0.0053	− 0.6364	0.7497	0.3999	− 0.5677	− 0.7476
Days 145	0.1514	− 0.0018	0.9953**	0.0979	− 0.9547*	− 0.9552*
Days 165	0.5051	0.2324	0.9279*	0.2177	− 0.8773	− 0.9439*

*$p < 0.05$; **$p < 0.0$

negatively related to the C/P ($P < 0.05$) and N/P ratios of detritus ($P < 0.01$). The leaves detritus of *T. bispinosa* exhibited the highest P concentration and the lowest C/P and N/P ratios, and its *k* value was the peak among the four kinds of detritus. The *k* values in the leaves detritus of *T. bispinosa* were 4.06-, 2.04-, and 1.35-fold higher than those of the stems (plus petiole) and leaves of *N. nucifera* and stems (plus petiole) of *T. bispinosa*, respectively. However, no significant correlation was found in our research between the *k* values with detritus N content and the C/N ratio. Similar conclusion was obtained by Hobbic (1996). Many studies have shown that N and P availability in the decomposing environment significantly affects the decay of detritus because decomposers utilize substrate nutrients (N and P) to meet their initial growth requirements (Liu et al. 2010; Balasubramanian et al. 2012; Li et al. 2013). The optimum C/N ratio is approximately 25 for microbial growth (Aerts et al. 1992; Cadish and Giller 1997; Li et al. 2012). In our study, the C/N ratio was changed from 19.16 to 38.73 with an average of 25.16, suggesting the C and N concentrations and their ratios were not the limiting factors for the growth of the decomposers. Furthermore, the net P mineralization ($C/P < 100$) and P immobilization ($C/P > 100$) on the basis of the C and P ratios were also reported (Enwezor 1976; Rejmánková and Houdková 2006). When P immobilization occurs, decomposers demand external P input to meet their initial growth requirements during the decomposition process (Balasubramanian et al. 2012; Li et al. 2013). In our study, the C/*P* values were higher than 100 with the exception of the leaves of *T. bispinosa*, mean relative shortage of P in the three other detritus and may limit their decomposition. Therefore, the significance of P-related indicators (not N-related indicators) for dry mass loss and decomposition rate of *T. bispinosa* and *N. nucifera* detritus were obtained in our study.

The decomposition rates obtained in the present study in the stems (plus petiole) and leaves detritus of *N. nucifera* (0.0030 and 0.0060 day^{-1}) were lower than the results obtained by Lan et al. (2012), who reported that decomposition rates are 0.0110 day^{-1} for the leaves and 0.0086 day^{-1} for the stems of *N. nucifera*. In addition, the $t_{95\%}$ of the detritus to be decomposed for the stems (plus petiole) and leaves of *T. bispinosa* were 332.53 and 247.09 days, which were longer than those reported by Singhal and Saraf (2000) (56 days for leaves and 77 for shoots) measured in a tropical pond. Climate factor differences may be the reason for the discrepancy of decomposition time for *T. bispinosa* because detritus were incubated on the north subtropical pond in this study. In addition, other external influencing factors, including nutrient availability, hydroperiod, and pH, were not considered because of the identical environmental conditions in the two plant detritus decaying sites during the entire decomposition period. Therefore, the differences in the dry matter loss and *k* values were majorly affected by species themselves and the differences in chemical and biochemical properties.

Furthermore, mass losses and detritus decay for *N. nucifera* and *T. bispinosa* in our study significantly changed with increasing decomposition time. This result can be confirmed by the results of two-way ANOVA (Table 1) and Pearson correlation analysis (Table 2). In the present study, except for the species- and tissue-specific effects, the decomposition time also had significant effects on detritus mass loss ($P < 0.0001$) (Table 1). In addition, the influence of initial detritus quality parameter to mass loss also changed with decomposition time (Table 2). Previous research confirmed the three distinct stages of aquatic macrophyte decomposition in the water, as follows: first, rapid mass loss in initial phases due to leaching, followed by decomposition and colonization by the decomposer, and then fragmentation by invertebrates and physical breakup (Petersen and Cummins 1974; Webster and Benfield 1986; Megonigal et al. 1996; Álvarez and Bécares 2006; Lopes et al. 2011). The results in this study and the findings of the previous studies have verified this process. Bonanomi et al. (2015) reported that, approximately 20% of starting mass rapid loss occurs in first 10 days of decomposition, then rate of mass loss declines for three submerged plant detritus. Álvarez and Bécares (2006) reported that 15% (winter) and 12% (summer) of total weight losses occur during the first 3 days of incubation. Lopes et al. (2011) found that the weight loss of *P. australis* and *Fucus vesiculosus* are faster at the beginning of the experiment than the other parts of the experiment, and their decomposition rates are also decreased with time. Lan et al. (2012) indicated that litter does not always decay at a constant rate; they observed six aquatic plants lose 13.33–64.27% of their initial weight during the first 6 days of incubation in the Baiyangdian Lake, China, Therefore, the mass loss is fastest at the beginning and becomes gradually slower with the decomposition time (Chimney and Pietro 2006).

Detritus chemistry changed and C and nutrient accumulation/release

In our research, the N concentration in plant tissues was rapidly decreased in the initial decomposition stage (day 6), then fluctuated in the latter decomposition stage (days 6–165), whereas the P concentration varied throughout the whole decomposition process. At the end of the experiment, the nutrient concentrations were all inferior to their initial levels. Our result is partially consistent with the findings of Li et al. (2014), who found that the N concentrations in plant materials are decreased quickly on the first 28 days and then remained almost unchanged until the end of the decomposition process. However, our result contradicted the P concentration results of Li et al. (2014), who reported that 30 to 80% of the P concentrations are decreased in the first 7 days, declined slightly from

days 7–28, and then remained with the similar values from days 28–70. Our results also contradicted the findings of Lan et al. (2012), who reported that the nutrient concentrations are varied significantly in the first 6 days and then rose continuously during the later decomposition period for six macrophytes in Baiyangdian Lake, China.

Previous research reported that the nutrient content is usually decreased due to the more rapid mass loss during the incubation period despite of a significant increase in the nutrient concentrations in plant materials (Lan et al. 2012). Therefore, only an increase or a decrease in the N and P concentrations does not reflect their storage and release/accumulation from the detritus into surrounding the water bodies. The *AI/RI* was used to express the N and P net accumulation/release status during detritus decomposition process (Chimney and Pietro 2006; Xie et al. 2004; Romero et al. 2005). *AI* value of greater than 1 indicated net nutrient accumulation, whereas the *AI* value of less than 1 indicated nutrient net release (Deng et al. 2016). In this study, the *AI* values of N and P were all less than 1 during the entire decomposition period for the stems (plus petiole) and leaves detritus of *N. nucifera and T. bispinosa*. These results indicated that the continuous net N and P were released and transferred from the plant detritus to the surrounding water body. Similar results were reported by Lan et al. (2012), who found that substantial amounts of nutrients are transferred from the aquatic plants to the lake water during the 140-day decomposition experiment. In addition, *AI* values of N and P from the leaves were lower than those from the stems (plus petiole) of two plants detritus. Lower *AI* values were also observed in *T. bispinosa* compared with the *N. nucifera*. This discrepancy in the *AI* values in the species- and tissue-specific may be attributed to the difference in the initial chemical and biochemical properties of detritus. In the present study, *AI* values of N and P were correlated with initial N and P contents and C/P and N/P ratios (Tables 7, 8, and 9) at a specific decomposition time. And those relationships also obviously changed with the decomposition time, indicated initial chemistry properties of detritus, to a certain extent, effect C and nutrient accumulation/release from detritus into water.

Conclusions

In conclusion, this study elucidated the decomposition dynamics of two aquatic macrophytes *T. bispinosa* and *N. nucifera* detritus by using the litterbag technique in a shallow lake. The dry mass loss and decomposition rates (k) had significant species- and tissues-specific differences. These differences were significantly affected by the initial chemistry parameters of detritus, particularly P-related parameters (P concentration and C/P and N/P rations). Furthermore, *AI* values indicated that more than 60% C, N, and P were transferred from the detritus to the water at the 165 day of the decomposition time under this experiment conditions compared with their initial values. This phenomenon resulted in the deterioration of water quality to a certain degree. In addition, species, decomposition time, and their interaction had significant effects on the detritus decomposition dynamics. However, the contributors of species and decomposition time were significantly varied based on their F values on the two-way ANOVA. Therefore, the control of species and decomposition time is important in the detritus decomposition process of *T. bispinosa* and *N. nucifera*.

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