Aerobic decomposition of *Myriophyllum aquaticum* (Vell.) Verdc. regulated by chemical composition of detritus and temperature

Decomposição aeróbia de *Myriophyllum aquaticum* (Vell.) Verdc. condicionada pela composição química do detrito e temperatura

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Abstract: Aim: This study described the oxygen consumption kinetics during the aerobic mineralization of *Myriophyllum aquaticum* evaluating the influence of detritus chemical composition and temperature during decomposition. **Methods:** The aquatic macrophyte was collected in the littoral region of the Monjolinho Reservoir (22° 00' S and 47° 54' W; SP, Brazil). In the laboratory, the plant fragments were subjected to leaching to extract the particulate fraction (POM). The mineralization chambers were set up (n = 12) with whole detritus or lignocellulosic matrix (i.e. fibers) in two phenological stages (senescent or green) under two temperature (16 and 25 °C). The concentrations of dissolved oxygen (DO) were measured periodically in the mineralization chambers during 80 days. The DO uptake was fitted to first-order kinetic model. **Results:** In the same condition of temperature and detritus type (green or senescent) the deoxygenation coefficient (k_D) was approximately 2 times higher in treatment with whole detritus compared with lignocellulosic matrix, which also showed higher C:P and smaller quantities of lignin in initial chemical composition of detritus. The Q_{10} has shown similarities between treatments, regardless of the chemical composition (whole or lignocellulosic matrix), however, showed differences on the phenological stage (ranged from 1.75 to 2.06). Concerning to the O/N, the process of mineralization of the organic to inorganic forms of nitrogen (nitrification) consumed more DO in treatments with lignocellulosic matrix (mean = 1%) compared to treatment with whole detritus (mean = 0.67%). **Conclusions:** The quality of detritus was the most important variable in the mineralization rate of macrophyte and the temperature played a secondary role.

Keywords: decomposition, whole detritus, lignocellulosic matrix, temperature, chemical composition of detritus.

Resumo: Objetivo: Este estudo descreveu as cinéticas de consumo de oxigênio durante a mineralização aeróbia de *Myriophyllum aquaticum*, avaliando os possíveis efeitos da composição química e da temperatura na decomposição. **Métodos:** A macrófita aquática foi coletada na região litorânea do Reservatório do Monjolinho (22° 00' S e 47° 54' O; SP, Brasil). Em laboratório parte dos fragmentos das plantas foram submetidos à lixiviação para extração da fração particulada (MOP). Foram montadas câmaras de decomposição (n = 12) contendo detrito íntegro ou matriz lignocelulósica (i.e. fibras) em dois estágios fenológicos (verde ou senescente) e submetidas a duas condições de temperatura (16 e 25 °C), totalizando 8 tratamentos. As concentrações de oxigênio dissolvido (OD) foram determinadas periodicamente nas câmaras durante 80 dias. Os resultados foram ajustados a um modelo cinético de primeira-ordem. **Resultados:** Numa mesma condição de temperatura e tipo de fragmento (verde ou senescente), o k_D foi aproximadamente 2 vezes maior nos tratamentos com detrito íntegro em relação aqueles somente com matriz lignocelulósica, que apresentou maior relação C:P e menores quantidades de lignina em sua composição química inicial. O Q_{10} mostrou similaridade entre os tratamentos, independente da composição química (integral ou fibras), porém, diferença em relação ao estágio fenológico da planta (variaram de 1,75 a 2,06). Com relação à estequiometria O/N houve um gasto maior de oxigênio no processo de mineralização do nitrogênio para as formas inorgânicas (nitrificação) nos tratamentos com detritos íntegros (média = 1%) em relação aos tratamentos com matriz lignocelulósica (média = 0,67%). **Conclusões:** A qualidade do detrito constituiu–se na variável mais importante na taxa de mineralização da macrófita, já a temperatura atuou como um fator secundário.

Palavras-chave: decomposição, detrito integral, matriz lignocelulósica, temperatura, composição química do detrito.

1. Introduction

The decomposition results in a change of detritus state and involves the processes of fragmentation, leaching and catabolic activity of microorganisms. The leaching refers to the transference of soluble materials to water; fragmentation provides an increase on detritus surface for microbial attack and catabolism contributes by the release of extra and intracellular enzymes for the detritus mineralization (Swift et al., 1979).

In aquatic ecosystems, during decomposition, the release of large quantities of organic constituents into water column in the dissolved (DOM) and particulate organic matter (POM) restore these compounds to the trophic web (Rothman and Bouchard, 2007). The DOM consists in a set of heterogeneous compounds whose metabolism and characteristics influence the availability of nutrients and the cycling of material and energy (Masifiwa et al., 2004). The DOM provides carbon to the microorganisms which are adhered to particles or free-living in the water column (Sala and Güde, 1999). The POM is constituted mainly by refractory compounds (e.g. lignin, cellulose and hemicellulose) that are resistant to rapid microbial decomposition and is characterized by being chemically stable with slow solubility (Wetzel, 1983). About 50 to 80% of the biomass of aquatic plants is composed by fibers (Bianchini Jr. and Cunha-Santino, 2008), and its decomposition show a strong dependence on structural materials which varies: among species, age, geographical location and growth conditions (Mansfield, 2005). The most active enzymes in the decomposition of aquatic plants are directly involved in the degradation of refractory compounds (Sinsabaugh et al., 2002). The metabolism associated with the POM and DOM provides the energy required for operation and metabolic stability of the whole ecosystem (Wetzel, 1990).

The decomposition of aquatic macrophytes is limited by microbial metabolism (Bünemann et al., 2004) and physicochemical conditions of the environment, such as chemical composition (e.g. lignin, cellulose and hemicelluloses; Bridgham et al., 2001) and temperature (Antonio and Bianchini Jr., 2002). According these authors, the temperature influences the rate of chemical and enzymatic reactions of microbial metabolism.

The cumulative oxygen consumption is an indirect measurement for assessing the oxygen demand of aerobic decomposition processes of aquatic macrophytes (Sciessere et al., 2007). The oxidative process, convert the detritus by catabolic action of microorganisms in small organic and inorganic molecules (Wetzel, 1983). The availability of DO affects the status of microorganism community and indirectly the metabolic routes used within mineralization (Cunha-Santino and Bianchini Jr., 2002). In this context, this study verifies the effects of temperature and chemical composition of detritus on the aerobic decomposition of aquatic macrophyte *Myriophyllum aquaticum* found in the littoral zone of an artificial subtropical reservoir.

2. Material and Methods

2.1. Description of the study area

The Monjolinho Reservoir (22° 00' S and 47° 54' W; SP, Brazil) is an artificial small shallow system situated in a subtropical region. It has an area of ca. to 4.69 ha, and average and maximum depth of 1.5 and 3.0 m, respectively (Regali-Seleghim, 2004). According to Köppen`s systematic, the region has two contrasting periods during the year, dry (April to September) and a hot rainy season (October to March). Depending on the period, the retention time of this system ranges from 2.1 to 22.9 days (Nogueira and Matsumura-Tundisi, 1994).

2.2. Bioassays

Samples of mature *M. aquaticum* (senescent and green) were collected manually at different stations of the littoral region of the Monjolinho Reservoir. In the laboratory, the plants were washed with tap water to remove periphyton, sediment particles and coarse material, oven-dried (45-50 °C) and sterilized by vertical autoclaving (Fabbe, model 103) at 121 °C, 1.0 atm for 15 minutes (Ward and Johnson, 1996). To obtain the lignocellulosic (LC) matrix were performed water cold extraction (4 °C) of entire detritus during 48 hours (adapted from Mϕller et al., 1999). The extraction was composed of plant fragments (previously sterilized) in deionized sterile water (proportion of 10 $g.L^{-1}$ DW). After the formation of leachate, the particulate fractions (LC matrix) were separated from the dissolved (DOM) by filtration and washing with deionized water. In sequence, the LC matrix were oven dried (45-50 °C) and stored before carrying out the experiment. Culture medium (modified from Xie, Yu and Ren, 2004) was prepared from a solution of micronutrients (Fe-EDTA = 0.60 $mg.L^{-1}$; H_3BO_3 = 0.39 $mg.L^{-1}$; $MnCl_2$. $4H_2O$ = 0.52 $mg.L^{-1}$; $ZnSO_4.7H_2O$ = 0.05 $mg.L^{-1}$; $CuSO_4.5H_2O$ = 0.02 $mg.L^{-1}$; $Na_2MoO_4.2H_2O$ = 0.01 $mg.L^{-1}$) and other composed of macronutrients (K_2SO_4 = 23.00 $mg.L^{-1}$; $CaCl_2$ = 20.00 $mg.L^{-1}$; $MgSO_4.7H_2O$ = 10.25 $mg.L^{-1}$; $NaNO_3$ = 9.65 $mg.L^{-1}$; $N\text{-}NO^-_3$ and NaH_2PO_4 = 39.20 $\mu g.L^{-1}$-P total).

Incubation chambers were set up with entire detritus (D) or LC matrix and with two phenological stages of fragments: green (G) or senescent (S). The culture medium and 400 µL of indigenous bacterial inocula of water from Monjolinho Reservoir were added to chambers. The water was filtered in ester cellulose membrane (Ø of pore =0.45µm; Millipore). The mineralization chambers (n = 96; previously wrapped with aluminum foil) were prepared using the entire detritus and LC matrix of *M. aquaticum* (300.00 $mg.L^{-1}$ DW) and the culture medium. Eight treatments were set up (n = 12), four with

entire detritus (two green fragment and 2 senescent) and four with the LC matrix (two green fragment and two senescent). The decomposition process was evaluated under 16 and 25 °C. Before the addition of culture medium to incubations those were oxygenated during 1 hour by filtered compressed air to keep DO near saturation.

2.3. Experimental analysis

The DO concentrations were measured periodically during 80 days by polarographic method (oximeter YSI, model 58; precision 0.03 $mg.L^{-1}$). In order to maintain the mineralization chambers under aerobic conditions, the bottles were oxygenated when the concentrations of DO reached values close to 3.00 $mg.L^{-1}$. The macrophyte chemical composition was measured in the initial of experiment and in final day of sampling (with entire detritus and LC) by spectrophotometry (Mackereth et al., 1978) for total phosphorus concentration and titulation method for total nitrogen concentration (Kjeldahl-N: Allen et al., 1974). The percentage of lignin was determined by acid hydrolysis (Allen et al., 1974) and cellulose by acid digestion (Clampton and Maynard, 1938). The organic matter content was determined by incineration of plant samples at 550 °C (Wetzel and Likens, 1991). The organic matter values were multiplied by 0.465 to obtain the values of carbon (Westlake, 1965).

The estimates of global stoichiometric relationship between the amount of oxygen consumed and the amount of oxidized organic nitrogen (O/N) were calculated using the ratios between the maximum consumption of oxygen (OC_{max}) and mineralized nitrogen during the oxidation process.

2.4. Mathematical modeling and statistical analysis

Kinetics fittings of oxygen consumption (OC) were performed using a non-linear regression, calculated with the iterative algorithm of Levenberg-Marquardt (Press et al., 1993). Under these procedures, the temporal changes in the oxygen consumption are described by Equation 1,

$$OC = OC_{max}\ (1 - e^{-k_D t}) \quad (1)$$

where: OC = consumed oxygen concentrations accumulated value ($mg.L^{-1}$); OC_{max} = maximum oxygen consumption ($mg.L^{-1}$), k_D = deoxygenation coefficient (day^{-1}) and t = time (day).

The time of half-life ($t_{1/2}$) from decomposition of the *M. aquaticum* was calculated according to Equation 2,

$$t_{1/2} = \frac{\ln 0,5}{-k_D} \quad (2)$$

From the variations of deoxygenation coefficients as a function of temperature is determined the values of Q_{10} (USEPA, 1985) (Equation 3).

$$Q_{10} = \left(\frac{K_2}{K_1}\right)^{\left(\frac{10}{T_2 - T_1}\right)} \quad (3)$$

where: Q_{10} = ratio between the reaction coefficients (in this case k_D) in increments of 10 °C, calculated from the temperature selected; k_1 = coefficient obtained in the reaction temperature T_1, k_2 = coefficient obtained in the reaction temperature T_2.

The results of accumulated oxygen consumption were analyzed individually for the eight treatments subjected to two temperatures, two detritus types (entire and LC) and two types of fragments (senescent and green), using the Kruskal-Wallis test (KW) followed by Dunn's multiple comparison to detect possible significant differences between treatments ($p < 0.05$).

3. Results

The kinetics of OC for aerobic mineralization of *M. aquaticum* is represented in Figure 1. The deoxygenation coefficients ranged from 0.0058 day^{-1} in treatment with senescent LC matrix (SLC) incubated at 16 °C to 0.0185 day^{-1} for the incubations with senescent entire detritus (SD) at 25 °C (half-life of 120 to 38 days, respectively - Table 1). Statistical analysis of KW did not indicate differences ($p > 0.05$) among treatments within the same temperature and type of detritus (entire and LC matrix). The same result was verified from the values of k_D. In the same condition of temperature and type of fragment (green or senescent), the k_D was approximately 2 times higher in treatments with entire litter compared with LC matrix, which showed higher C:P (ranging from 2.139 to 2.180) and smaller quantities of lignin (ranging from 37.08 to 42.76%) in their original chemical composition (Table 2).

For the kinetic fitting was considered as a condition of maximum OC the mineralization chambers incubated under 25 °C, with a smaller degree of litter decomposition (green). Using this criterion, the highest value of

Table 1. Parameters obtained from the kinetic model of aerobic mineralization of *M. aquaticum*. OC_{max} = maximum oxygen consumption; k_D = deoxygenation coefficient of, $t_{1/2}$: time of half-life, r^2 = determination coefficient.

Treatments	OC_{max}	error	k_D	error	r^2	$t_{1/2}$
GD 16 °C	670.62	-	0.0103	0.0001	0.99	67
SD 16 °C	599.99	-	0.0096	0.0001	0.99	72
GD 25 °C	670.62	21.36	0.0171	0.0009	0.99	41
SD 25 °C	599.99	19.66	0.0185	0.0010	0.99	38
GLC 16 °C	670.62	-	0.0063	0.0001	1.00	111
SLC 16 °C	433.73	-	0.0058	0.0001	0.99	120
GLC 25 °C	670.62	-	0.0105	0.0001	1.00	66
SLC 25 °C	433.73	13.39	0.0109	0.0005	1.00	63

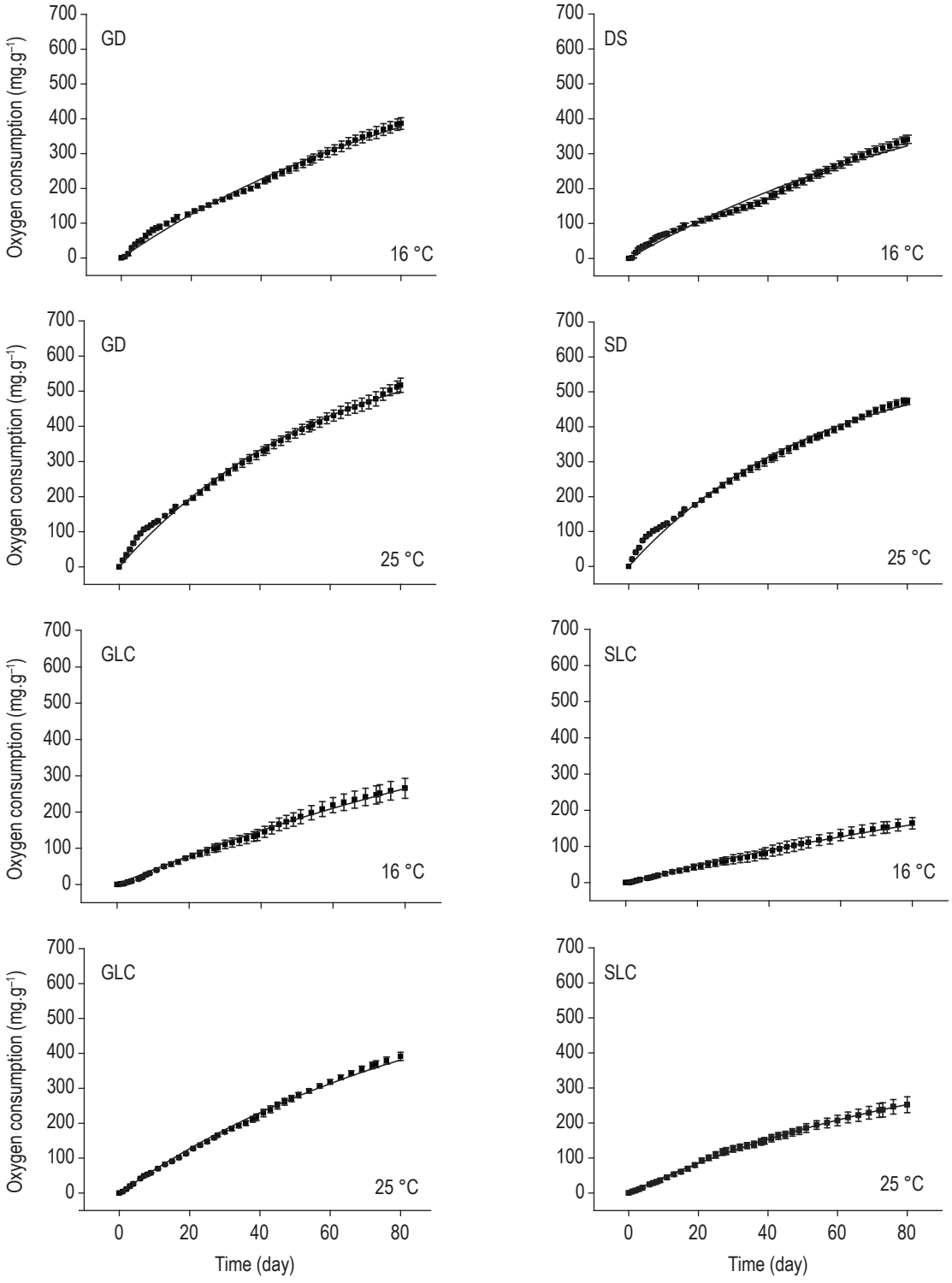

Figure 1. Kinetics of oxygen consumption during mineralization of *M. aquaticum* (GD/SD = green/senescent detritus. GLC/SLC = green/senescent lignocellulosic matrix).

OC (OC_{max}) was 670.62 mg.g^{-1} DW, adopted also in the mineralization of entire and LC treatment with green fragment (GD and GLC) and maintained at both temperatures 16 and 25 °C. The lower value was 473.73 mg.g^{-1} DW in the treatments with LC with senescent fragment at 16 and 25 °C ($p > 0.05$). The calculations for obtaining the Q_{10} showed similarity between the treatments, regardless of the type of litter, but differences in relation to phenological stage of the plant (green or senescent), the values ranged from 1.75-2.06. The fragments of macrophytes independent of phenological stage showed a predominance of particulate organic matter (POM) for soluble fractions

Table 2. Initial chemical composition of the green (GD) and senescent (SD) detritus and green (GLC) and senescent (SLC) lignocellulosic matrix.

%	SD	GD	SLC	GLC
Leachate	27.85	23.76	-	-
POM	72.16	76.24	-	-
IM	10.64	7.54	8.00	6.22
OM	89.36	92.47	92.00	93.78
Lignin	33.49	29.82	37.08	42.76
Cellulose	23.78	23.98	26.00	23.64
Nitrogen	1.87	2.19	1.66	2.01
Phosphorus	0.09	0.09	0.02	0.02
C:N	22.22	19.60	25.77	21.70
C:P	461.67	477.78	2139.00	2180.50

whose average was equivalent to 25.8%. The POM was 72.16-76.24% of the entire litter, the percentage of carbon between 42.78-43.61% and inorganic matter between 6.22-8.00% of plant material.

A difference between the concentrations of organic phosphorus of particulate (0.02%) and entire (0.09%) fractions was observed. This variation was not checked on the content of organic nitrogen. Approximately 43.68% of N was mineralized on treatments with entire detritus and only 19.84% in the amount mineralized LC matrix treatments during the 80 days of decomposition. The overall stoichiometry O/N showed a higher expense of DO in the mineralization of nitrogen to inorganic forms (nitrification) in treatments with entire litter (mean = 1%) compared to the others treatments (mean = 0.67%).

4. Discussion

The high values of the determination coefficients showed that the used kinetic model (1st order) was appropriate to describe the kinetics of OC for aerobic oxidation processes of *M. aquaticum*. From the kinetic point of view, independent of treatments (entire detritus or LC matrix), the change in OC were initially rapid and intense, with no tendency to stabilize. The pattern of decomposition of the aquatic macrophyte showed an OC more intense at the beginning followed by a more gradual increase because of the slow degradation of refractory fractions (more resistant) of organic matter, composed of structural carbohydrates associated with the cell wall of plants, such as hemicellulose, cellulose and lignin (Moore et al., 2004). The decomposition occurs primarily by leaching, with the intense release of soluble compounds in the first 24 hours (Bianchini Jr. et al., 2002). At this stage, approximately 30% of the plant material can be leached without microbial action (Gaur et al., 1992). The rapid release of DOM at the beginning can also be attributed to used methodology (i.e. dried detritus). In nature, the senescense is a gradual and the intensity of DOM liberation was probably overestimated. The second process is the colonization of the material by microorganisms (Singhal et al., 1992), which produces enzymes (e.g. cellulases and xylanase) essential for the decomposition of vascular material. The compounds more resistant are lesser accessed by microbiota, meaning in kinetics point of view, a substances that tend to limit the rate of cycling of total organic carbon of plant tissues (Komínková et al., 2000). Shilla et al. (2006) observed this same pattern in studies of this nature for the aquatic macrophyte *Myriophyllum sulsagineum;* the loss of mass of aquatic macrophytes has a quick initial oxygen consumption associated with bacterial colonization of the detritus.

Thus, detritus are differentiated according to their potential for degradation, providing a labile fraction and/or soluble and other refractory (Asaeda et al., 2000). The oxidation of labile fractions is characterizes by a rapid loss of weight, while the refractory portion may decrease from 10 to 20 times more slowly (Gillon et al., 1994). In this context, the high deoxygenation coefficients (k_D) obtained from the parameterization of the kinetic model with entire detritus treatment at 25 °C confirm their labile nature, with rapid degradation of the protoplasmatic compounds more easily available to the microbial community. Temperatures below 15 °C encourage the growth of psichrophilic bacteria (Farrell and Rose, 1967), so the low values of k_D found in treatments maintained at 16 °C with only LC matrix, suggest the occurrence of bacterial communities not adapted to that temperature and interference of the low quality of detritus (higher levels of lignin and low concentrations of P) in the mineralization of organic matter. The quality of the litter is defined by chemical composition and structural morphology influences the degradability of different types of detritus of aquatic macrophytes (Enríquez et al., 1993).

During decomposition, the litter is changed by intrinsic regulators factors (e.g. content of lignin, phosphorus and nitrogen). The low lignin content and high concentrations of phosphorus and nitrogen promote high rates of decomposition (Magee, 1993). In treatments with entire detritus, the concentrations of phosphorus were higher compared with the treatments with LC matrix and the levels of lignin were lower resulting in high potential for biodegradation (high k_D). The effect of microbial degradation in regulating the concentrations of DOM in aquatic ecosystems is directly related to k_D (Cunha-Santino, 2003). Refractory components such as cellulose and lignin are generally the largest part of plant biomass can reduce the microbial activity (Longhi et al., 2008). The rapid decomposition in the treatments with entire litter at 25 °C ($t_{1/2}$ = 38 days to senescent material and 41 days to green material) characterized this event as a short-term and can be explained by the lower percentage of lignin (ranging from 29.82 to 33.49%). Regarding the chemical composition of plant material, the aquatic macrophytes have on average 39% carbon,

1.9% nitrogen and 0.26% phosphorus (Bianchini Jr. and Cunha-Santino, 2008), corroborating with that found in this study, except for phosphorus which was significantly lower percentage (0.09%). The high microbial activity results in high rates of decomposition when associated with low C:P (Rejmánková and Houdková, 2006). Nichols and Keeney (1973) observed a rapid loss of phosphorus from the litter in contrast to the tendency to accumulation of nitrogen, corroborating the pattern found in this study.

Concerning the plant phenological stage, the senescent fragments showed a smaller proportion of phosphorus. This is because, in submerged senescent plants, the labile P is lost rapidly (Davis III et al., 2006), by translocation via phloem or leaching. During the senescence the plant material is transformed into DOM and microbial biomass available to higher trophic levels (Moran and Hodson, 1989). According to Howard-Williams and Davies (1979) an increase of 10 °C may increase the bacterial metabolism by up to 3 times during decomposition, but in studies by Straškraba (1999) with bacterial decomposition in sediment that value was higher (3.84). The different temperatures at which the treatments were submitted (16 and 25 °C) showed increased biological activities in about 2 times for treatments with detritus and LC matrix. This increase also occurred in studies of Cunha-Santino (2003) with litter from *Utricularia breviscapa*. This suggests a greater sensitivity of microbial communities that act in the degradation of senescent litter (2.06 to 2.04) in comparison with microbiota that mineralized green litter (1.75 to 1.77). According Katterer et al. (1998), Q_{10} values are close to 2 in the temperature range from 5 to 35°C. In both cases (entire detritus and LC matrix) were observed increases in microbial activity as the temperature increases. Among all the conditioning factors of the decomposition, the high temperature characteristics of subtropical aquatic environments are probably responsible for the rapid breakdown of litter and water recycling plant biomass (Esteves and Barbieri, 1983).

An oxidation of labile fractions prevailed at the beginning, generating high demand for oxygen. Moreover, during this period, the increments of oxygen consumption were probably also related to the oxidation of nitrogen compounds and secondarily to the mineralization of refractory compounds. The stoichiometric is an indirect way to predict the routes of metabolic activities of microorganisms (Cunha-Santino et al., 2002). In this context, it was possible to establish a stoichiometric balance between N mineralized and OC in the process of nitrification. Based on this relation, a greater amount of N mineralized in the experiments with entire litter in relation to LC matrix detritus, suggest that the microbial oxidative processes that prevail in the entire litter showed more resources to process the nitrogen. The other part was converted into biomass (i.e. immobilized). The increase in concentrations of N in the detritus during decomposition possibly due to increased bacterial biomass and/or large quantity of secreted exoenzymes by microorganisms attached to detrital particulate matter (Pagioro and Thomaz, 1999).

In this way, the aquatic macrophytes contributes for immobilization and effective cycling of nutrients to aquatic ecosystems through aerobic mineralization, which may represent events in the short or long term, depending on the chemical composition of detritus and temperature variation of the aquatic ecosystem. In this context, based on the experimental conditions of this study, the quality of litter was the most important factor in mineralization of *M. aquaticum*, providing quickly (high k_D) and large quantities of inorganic N to aquatic microbiota. The temperature was a secondary factor, with differences in the values of Q_{10} on the microbial metabolism (equivalent to 17%).

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