**Original Paper**

# Influence of Temperature and Water Conditions on the Mineralization Rate of Tropical Peat

Nagamitsu Maie[1*], Masahiro Maeda[1], Aya Murouchi[1], Lulie Melling[2], Rieko Takamatsu[1], Faustina Sangok[2,3], Wataru Kakino[1], Hajime Tanji[1], Akira Watanabe[3]

[1] School of Veterinary Medicine, Kitasato University, 23-35-1 Higashi, Towada, Aomori 034-8628, Japan

[2] Sarawak Tropical Peat Research Institute, Lot 6035, Kota Samarahan Expressway 94300 Kota Samarahan, Sarawak, Malaysia

[3] Graduate School of Bioagricultural Sciences, Nagoya University, Chikusa, Nagoya 464-0814, Japan

*Corresponding author: Tel: +81-176-23-4371 (ext. 480); Fax: +81-176-23-8703; E-mail: maie@vmas.kitasato-u.ac.jp

## Abstract

Tropical peat is woody peat different from sedge and moss peat in temperate-boreal region. As such, its decomposition characteristics can be different from the latter. Here, several factors affecting mineralization rate of tropical peat were investigated in terms of forest type (Mixed peat swamp (MPS) and Alan Bunga (ABg)), temperature (25°C and 35°C), and water content (60%, 80%, and 98%), in a laboratory incubation experiment. Peat soil samples were incubated for 1 year with periodical gas sampling. Cumulative amounts of $CO_2$ produced from MPS and ABg soils during 1-year period ($\Sigma CO_2$) were 0.6–3.2% of peat C (hereafter abbreviate as %) and 2.4–8.1%, respectively, showing ABg soil decomposed 2.5–5.3 times faster than MPS soil when incubated at an identical conditions. $Q_{10}$ values ranged from 0.85 to 2.4. Water content influenced bi-directionally to the decomposition rate of peat depending on the case situation.

**Keywords**: Mineralization rate, Oxygen, Peat quality, Temperature, Tropical peat, Water content

## Introduction

Peatland accumulates 450–550 Pg of carbon (C) as humus, which is equivalent to 70% of atmospheric C stock (Parish et al. 2008). Peatland can be a significant C source when the environment changes through land-use change and global warming, etc. (Laiho 2006). Therefore, many studies have been conducted to unveil the influence of environmental changes on the decomposition rate of peat and its controlling factors in boreal climate (Silvola et al. 1996; Laiho 2006 and references herein). However, while tropical peatland is estimated to accumulate 88.6 Pg C, accounting for 15–19% of global peat C pool (Page et al. 2011), comparatively little studies have been conducted on the same topic (e.g. Murayama and Baker 1996; Hoyos-Santillan et al. 2016).

Tropical peat accumulates under tropical peat swamp forests (TPSFs). It is woody peat that contains trunks, branches, and coarse roots in dark brown amorphous organic materials. Several types of TPSFs dominate on a peat dome, which generally shift with the distance from a riverbank in a concentric fashion (Lulie 2016). In Sarawak, Malaysia, mixed peat swamp (MPS) dominates at the neighboring riverbanks, which shifts into Alan

Batu (ABt), and then Alan Bunga (ABg) forests toward the interior. The groundwater level and nutrient status of tropical peatland also change with the distance from a riverbank. As such, physicochemical characteristics of peat formed under respective forests are different among forest types (Melling 2016, Sangok et al. 2017).

Since 1960s, countries such as Indonesia and Malaysia in Southeast Asia have developed tropical peatland into oil palm plantation due to limited acreage of arable dry field. On reclamation of TPSF to oil palm plantation, original vegetation is clear-cut and groundwater table is lowered to ca. 70cm below the surface. In such a situation, concerns arise about these environment changes may accelerate the decomposition of peat. To answer this question and to contribute to the better management of oil palm plantation, it is important to better understand the decomposition rate of peat and the major influential factors under developed environment.

Sangok et al. (2017) conducted a decomposition incubation experiment in which mesocosm columns packed with peat samples freshly collected from native tropical swamp forests were incubated at an oil palm plantation for 3 years. They found that the quality of tropical peat was the crucial factor that influence the mineralization rate of peat as is the case with boreal peat. However, it was not clear from their experiment about how temperature and water conditions, which are important factors as influencing microbial activity, affected the rate of mineralization. In this research, to better understand the influence of these two factors to the rate of mineralization of tropical peat, we conducted laboratory experiment, which enabled to incubate peat samples under fixed conditions. In the experiment, two different peat samples, Mixed peat swamp (MPS) and Alan Bunga (ABg), were incubated under controlled temperature (25°C and 35°C) and water content (60%, 80%, 98%) for 1-year, and cumulative amount of $CO_2$ produced ($\Sigma CO_2$) was compared between treatments.

## Materials and Methods

### ***Peat samples***

Peat soil samples were collected at Maludam National Park, the largest preserve of native tropical swamp forests in Sarawak, Malaysia. Vegetation zone shifts along with the distance from riverbanks, as is often the case with tropical peat swamps: MPS is formed neighboring riverbanks and ABt is formed more interior. Vegetation of MPS is mainly composed of *Gonystylus bancanus*, *Dactylocladus stenostachys*, *Copaifera palustris*, and 4 *Shorea spp.*, while that of ABg is entirely dominated by *Shorea albida* (Melling et al. 2016). Subsurface peat samples (20–40 cm below the surface) were collected under MPS forest (1°25'N, 111°07'E) and ABg forest (1°27'N', 111°09'E). Peat soil samples used were identical to those used in Sangok et al. (2017) and their chemical properties, cited from Sangok et al. (2017), are listed in Table 1. Alkyl C/O-alkyl C ratio of MPS peat is higher than ABg peat, suggesting the former is more microbially decomposed than the latter (Baldock et al. 1997).

### ***Incubation experiment***

Peat soil samples were dried to a moisture level of 50–60% at room temperature and passed through a 2-mm mesh sieve. Peat soil samples amounting to 1 g on dry weight basis were put into 100-ml Erlenmeyer flasks. The flasks were capped tightly with double-layer butyl rubber plug (Maruemu Corp., JAPAN) and incubated for 1-year at 25°C or 35°C in temperature-controlled incubators. Water content was regulated at 60%, 80%, and 98% on wet soil weight basis for each temperature. The 98% moisture treatment was prepared by adding 50 ml of ultrapure water (submerged conditions). Each treatment was prepared in 4 replicates. Samples with different treatments were notated by connecting treatment conditions with hyphen, e.g., MPS-60%-25°C stands for the MPS soil incubated at a water content of 60% at 25°C. During the incubation period, a 4-ml portion of gas inside the flask was collected once a week (until 84-d) or once a month (after 84-d) using a 10-mL air-tight syringe and transferred into a 4-ml pre-evacuated glass vial (Nichiden-Rika glass co., Tokyo, Japan) for determining the amount of $CO_2$ produced. After each gas sampling, the inner gas was replaced by $CO_2$-free air ($N_2$ 79%, $O_2$ 21%) and ultrapure water was added to maintain the setting value within 1% error.

### *GC analysis*

Concentration of $CO_2$ in the gas samples was measured by introducing 100-ml aliquot to a gas chromatograph (Shimadzu GC-2010 Plus, Kyoto, Japan) equipped with a Barrier Ionization Discharge (BID) detector.

### *Statistics*

Cumulative $CO_2$ amounts were compared statistically among the treatments using Tukey-Kramer test (JMP 9.0.3 SAS Institute Inc.).

## Results

### *Periodical change of $CO_2$ production rate*

Periodical changes in the cumulative $CO_2$ production are shown in Fig. 1. The pattern of cumulative $CO_2$ production followed an exponential rise to maximum relationship in respect to time for all the treatments with 60% or 80% water content. On the other hand, it followed a sigmoid curve for all the treatments with 98% water content. Since the water contents of MPS and ABt samples just before using the incubation experiments were 51% and 61%, respectively, microbe could have needed a lag phase until it adapted to a new environment for treatments with 98% water content. Larger variances were observed between replicates for ABg-35°C, which could be due to micro-scale heterogeneity of dissolved oxygen and peat quality among replicate (Pedersen et al. 2015). Cumulative amount of $CO_2$ emitted during a 1-year period ($\Sigma CO_2$) accounted for 0.6‐3.2% and 1.3‐2.7% of total peat C (hereafter abbreviate as %) at 25°C and 35°C, respectively, for MPS soil (Table 2). These values for ABg soil samples were 2.4‐7.9% and 5.9‐8.1% at 25°C and 35°C, respectively.

### *Influence of temperature on $\Sigma CO_2$*

Table 2 shows the $\Sigma CO_2$ of each treatment and the ratio of $\Sigma CO_2$ between two treatments. The $\Sigma CO_2$ increased as the temperature increased from 25°C to 35°C when the water content was 60% or 80%. The rate of the increase in $\Sigma CO_2$ with increasing temperature by 10°C ($Q_{10}$) was higher for the ABg soil than in the MPS soil and higher in the lower water content, with the maximum value of 2.4 for the ABg-60% treatment. Note the $\Sigma CO_2$ was lower for the treatments incubated at 35°C than 25°C when incubated at the water content of 98%, leading to the $Q_{10}$ values less than 1 for both MPS and ABg soils (Table 2). This was probably due to the shift of peat environment from aerobic to anaerobic conditions.

### *Influence of forest type on $\Sigma CO_2$*

The $\Sigma CO_2$ of the ABg soil was 2.5–5.3 times larger than that of the MPS soil when the incubation conditions are identical (Table 2). The difference between the two soils was the largest when water content was 80%.

### *Influence of water conditions on $\Sigma CO_2$*

When the MPS and ABg soils were incubated at 25°C, $\Sigma CO_2$ increased by 5.1 and 3.3 times, respectively, as the water content increased from 60% to 98% except for ABg-98%-35°C (Table 2). The increasing rate of $\Sigma CO_2$ with increasing water content from 60% to 98% was smaller at 35°C, i.e., by 2.1 and 1.4 times for the MPS and ABg soils, respectively, except for the ABg-98%-35°C treatment, where there was no significant difference in $\Sigma CO_2$ from the ABg-60%-35°C.

## Discussion

### *Influence of temperature and C type on the rate of peat mineralization*

According to Sangok et al. (2017), the rate of the decomposition of peat in a 3-year field incubation at an oil palm plantation in Sarawak was 3.2% for the MPS soil and 6.4% for ABg soils, where the soil temperature at a depth of 5 cm ranged from 23 to 33°C. The values were intermediate among the rate of the peat decomposition observed in this study, suggesting that the present result reflected the variation in the peat decomposition rate in the field. When looking at the influence of temperature, $Q_{10}$ values of our results, ranging from 1.6 to 2.4 except for the treatment with water content of 98%, were similar with those reported for peats and soils in various region (2.4, Lloyd and Taylor (1994); 2.4 with a range of 1.3–3.3, Raich and Schlesinger (1992)). Variation in the $Q_{10}$ values can be brought about by the difference in the C quality and temperature range (Inglett et al. 2012). Clein and Schimel (1995) reported the $Q_{10}$ values can increase as high as 23.4 in boreal region. As such, increasing in the soil temperature increases $CO_2$ production rate at a higher rate for boreal peatland than tropical peatland. It is noteworthy that soil environment in terms of $O_2$ conditions can change by temperature increase, which lead to adverse effect on the soil microbial activity as is described below.

Peat quality is often ascribed to the most significant factor that influences mineralization rate or more accurately, mineralizable C pool for boreal peat (e.g. Hogg et al. 1992; Laiho 2006; Grover and Baldock 2012). In our experiment, the rate of mineralization of ABg soil was 2.5–5.3 times faster than MPS soil. According to Bridgham and Richardson (1992), peats that have already been exposed to long periods of aerobic decomposition may be more resistant to further decomposition. The groundwater table of ABg forest (from -6.9 to -7.6 cm) was higher than that of MPS forest (from -13.3 to -20.7cm) (Sangok et al. 2017), and alkyl C/O-alkyl C ratio of the ABg soil sample was lower than that in the MPS soil sample (Table 1). Therefore, the ABg soil is considered to have undergone less microbial decomposition processes (Baldock et al. 1997; Grover and Baldock 2012) and contained a larger amount of readily oxidizable C under aerobic conditions. In this experiment, we confirmed that chemical characteristics of soil is major influential factor that control the decomposition rate of tropical peat.

### *Bidirectional influence of water content on the rate of peat mineralization*

In peatland with a certain level of microbial activity and stagnant water, transfer of molecular oxygen ($O_2$) is limited by low $O_2$ diffusion coefficient and $O_2$ consumption at the upper layer. Under anaerobic conditions, decomposition of submerged peat is restricted due to prevention of phenol oxidase from eliminating phenolic compounds that inhibit biodegradation (Pind et al. 1994; Freeman et al. 2001). However, in our experiment, air inside the flask was regularly replaced with $CO_2$ free air ($N_2$, 78%; $O_2$, 22%), and as such, $O_2$ may not have been consumed to the level that constrain the mineralization of peat at 25°C. Under such aerobic condition, water promotes transportation/diffusion of substrates/enzymes and mobility of microbes, resulting in the higher decomposition rate at a higher water content (Stark and Firestone 1995; Waddington et al. 2001). Note that the response of mineralization rate to the change in water content varies depending on peat quality (Husen et al. 2014). At a higher temperature (i.e. 35°C), however, $\Sigma CO_2$ was lower in the 90%-35°C treatment than in the 80%-35°C treatment (Fig. 1; Table 2). This was probably due to exhaustion of dissolved $O_2$ because (1) the saturated-dissolved $O_2$ is smaller at a higher temperature (8.11 $mgO_2\ L^{-1}$ at 25°C vs. 7.04 $mgO_2\ L^{-1}$ at 35°C), (2) $O_2$ diffusion coefficient is smaller at a higher water content ($1.98x10^{-5}\ m^2s^{-1}$ in air vs. $1.9x10^{-9}\ m^2s^{-1}$ in water; Hillel 1998), and (3) microbial activity (soil respiration) is greater at a higher temperature under aerobic conditions (Pietikäinen et al. 2005). This interpretation is coincident with a conceptual model proposed by Skopp et al. (1990), in which microbial activity was defined as a function of soil water content that controls substrate diffusion rate and $O_2$ diffusion rate. In their model, a higher water content brings a higher substrate diffusion rate and a lower $O_2$ diffusion rate. Therefore, until optimum water content for $CO_2$ production, the rate of peat decomposition increases as the water content increases. A good example of this can be seen in a depth profile of decomposition rates in peat: a secondary or even primary decomposition peak can exist at the range of the water level variation in hammock of boreal peat (Laiho 2006). Therefore, water content is considered to have bidirectional effect on the rate of decomposition of tropical peat as is the case with temperate-boreal peat, while the saturated-dissolved $O_2$ and as such the optimum water content for $CO_2$ production is lower for tropical peat compared with temperate-boreal peat.

## *Implication*

In an oil palm plantation, $CO_2$ flux from soil has been considered to be strongly controlled by water-filled pore space (Melling et al. 2005). Peat compaction, which is a common practice in reclaiming of tropical wetland to oil palm plantation in Malaysia, increases bulk density, lowers porosity of surface layer, and thus increases water-holding capacity of soil (Melling and Henson 2011). Thus, soil compaction may decelerate the rate of peat decomposition at deep layer by lowering diffusion of $O_2$. Future research is awaited to unveil the changes in the soil environment by soil compaction to contribute to the sustainable management of tropical peatland in terms of peat decomposition and $CO_2$ emission.

## *Conclusion*

We confirmed that the differences in the chemical properties of humus and water content greatly influenced the rate of mineralization of tropical peat, as is the case with temperate-boreal peat. Effect of temperature on the rate of mineralization of tropical peat ($Q_{10}$=1.6-2.4; aerobic conditions) was also similar with those in other region. Since water content exerts bidirectional influence on the rate of decomposition of tropical peat depending on the case situation, influence of water content on the decomposition rate of peat need to be carefully examined.

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## Figure caption

**Figure 1**. Periodical changes in the cumulated $CO_2$ production from peat soil samples incubated at different conditions. Water content: White circle, 60%; grey triangle, 80%; and black diamond, 98%.

**Figure 2**. Comparison of cumulated $CO_2$ production between treatments. Different letters on plots indicate the presence of statistically significant differences between treatments ($p < 0.05$).

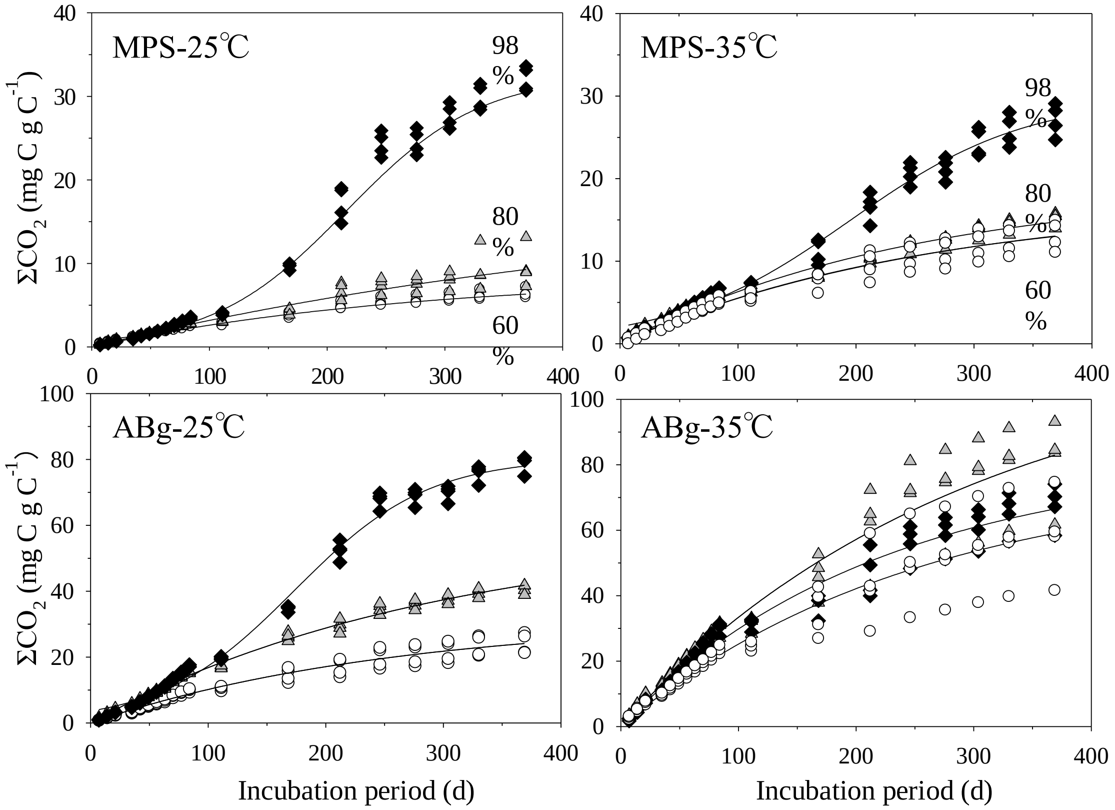
MPS-25℃
MPS-35℃
ABg-25℃
ABg-35℃
98 %
80 %
60 %
$\Sigma CO_2$ (mg C g C$^{-1}$)
Incubation period (d)
0
10
20
30
40
60
80
100
200
300
400

Fig. 1

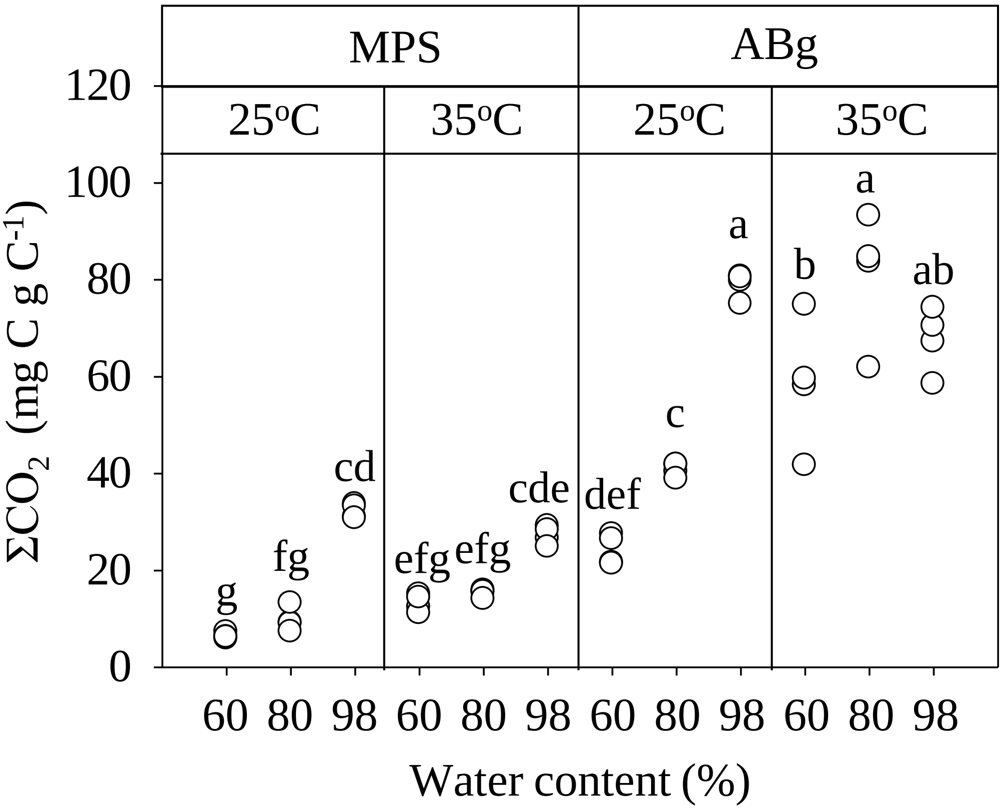
MPS
ABg
25oC
35oC
25oC
35oC
$\Sigma CO_2$ (mg C g C$^{-1}$)
0
20
40
60
80
100
120
g
fg
cd
efg
efg
cde
def
c
a
b
a
ab
60
80
98
60
80
98
60
80
98
60
80
98
Water content (%)

Fig. 2

330

Table 1 Chemical properties of peat samples 1)

| | MPS | ABg |
|---|---|---|
| pH ($H_2O$) | 3.6 | 3.6 |
| Loss on ignition (%) | 98 | 99 |
| Total C (g kg$^{-1}$) | 53.5 | 52.0 |
| Total N (g kg$^{-1}$) | 20 | 13 |
| C/N | 27 | 40 |
| Carbon composition based on $^{13}$C CPMAS NMR | | |
| %Alkyl C (0–45ppm) | 32.9 | 21.3 |
| %O-alkyl C (45–110ppm) | 26.4 | 36.5 |
| %Aromatic C (110–160ppm) | 26.9 | 32.5 |
| %Carboxyl C (160–190ppm) | 12.5 | 8.8 |
| %Ketone C (190–220ppm) | 1.3 | 0.9 |
| Alyl C/O-Alkyl C | 1.25 | 0.58 |

1) Sangok et al. (2017)

Table 2 $\Sigma CO_2$ from each treatment and their ratios

| Treatment | $\Sigma CO_2$ (mg C $g^{-1}$ C $y^{-1}$) | $\frac{35^\circ C}{25^\circ C}$ ($Q_{10}$) | $\frac{ABg}{MPS}$ | $\frac{80\% \text{ or } 98\%}{60\%}$ |
|---|---|---|---|---|
| MPS-60%-25°C | 6.4 ± 0.6 g1) | - | - | |
| MPS-80%-25°C | 9.6 ± 2.5 fg | - | - | 1.5 ± 0.3 |
| MPS-98%-25°C | 32 ± 1 cd | - | - | 5.1 ± 0.1 |
| MPS-60%-35°C | 13 ± 2 efg | 2.1 ± 0.2 | - | |
| MPS-80%-35°C | 15 ± 1 efg | 1.6 ± 0.3 | - | 1.2 ± 0.1 |
| MPS-98%-35°C | 27 ± 2 cde | 0.85 ± 0.1 | - | 2.1 ± 0.2 |
| ABg-60%-25°C | 24 ± 3 def | - | 3.8 ± 0.2 | |
| ABg-80%-25°C | 41 ± 1 c | - | 4.2 ± 0.3 | 1.7 ± 0.1 |
| ABg-98%-25°C | 79 ± 3 a | - | 2.5 ± 0.1 | 3.3 ± 0.1 |
| ABg-60%-35°C | 58 ± 14 b | 2.4 ± 0.3 | 4.5 ± 0.3 | |
| ABg-80%-35°C | 81 ± 13 a | 2.0 ± 0.2 | 5.3 ± 0.2 | 1.4 ± 0.3 |
| ABg-98%-35°C | 67 ± 7 ab | 0.86 ± 0.1 | 2.5 ± 0.1 | 1.2 ± 0.3 |

1)Levels not connected with same alphabetical letter indicate significant differences ($p<0.05$).