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DETECTION OF ACOUSTIC EMISSION CHARACTERISTICS OF PLANT ACCORDING TO WATER STRESS CONDITION

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Abstract

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Utilization of acoustic emission (AE) technique for understanding of plant reaction due to the change of environmental conditions was performed in this research. The object of present experiment is to study the acoustic emission characteristics acquired from water-stressed plant and well-watered plant. In this study, two specimens of maize were chosen to be test under controllable environment. The outcomes of this experiment revealed that a large number of AE signals detected from plant were able to be noticed, especially in counts number of AE signals, when the plant was under water stress condition, whereas this situation of AE signals did not appear on plat with well water condition. Moreover, , multiple regression calculated to find the correlation between AE parameter received from maize and environmental parameters presented that air temperature was the most important parameter affecting to the RMS value as an AE parameter showing cavitation event of test plant. As these results, AE signals detected from test maize is capable of indicating its water stress condition. Therefore, using of AE method for monitoring the plant is considerably interested as state-of –art technique for increasing productivity, especially in agricultural field.

Keywords: acoustic emission, Multiple-regression, plant transpiration, cavitation

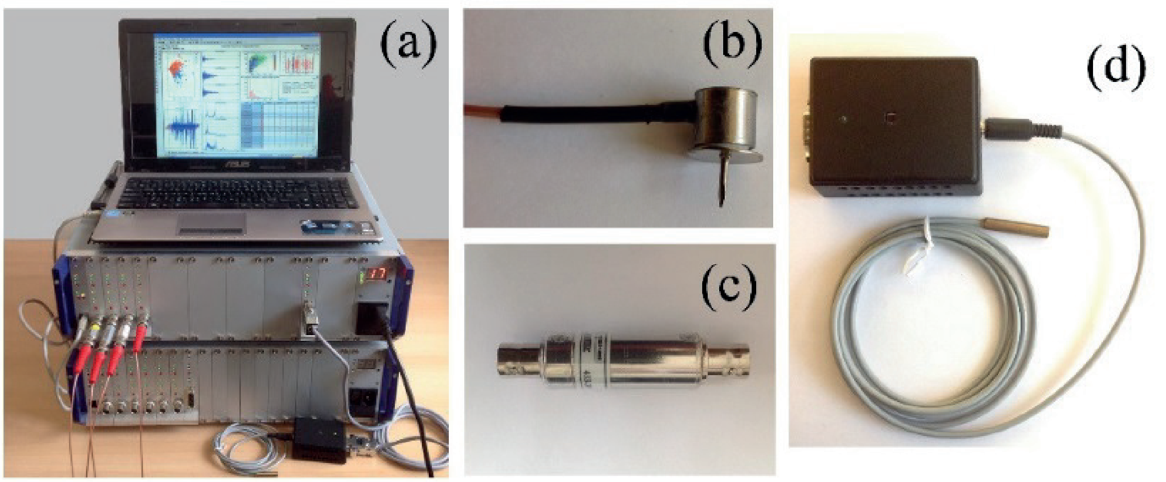
INTRODUCTION

Non-destructive testing (NDT) is the analysis techniques used to inspecting, testing, or evaluating various duties and researches in science and industry fields without destroying the serviceability of the part or system. Acoustic emission (AE) testing is advantageously one method of non-destructive testing since it allows early detection of internal defects in a finished or semi-finished product that may cause breakdown of a structure after a specific time of operation. Base on acoustic emission testing in researches, many researchers using AE testing have focused on engineering tasks, for example, evaluation of corrosion process using acoustic signals with quality tools was reported by Dostál P. *et al.* (2014), and observation of AE signals of AISI type 316 stainless steel during tensile test was uncovered by Haneef T. *et al.* (2015). Nevertheless, AE testing was not only utilized in engineering sections, but it was also applied in agricultural field, particularly in laboratory parts. As can be found in agricultural researches, using acoustic emission method has been carried out by some researchers for studying on drought stress condition of plants to achieve the specific proposes such as improving crop management, controlling irrigation system, and increasing plant production. Basically, drought stress of plant results from decrease of xylem pressure and increased frequency of cavitation (Barigah *et al.*, 2013). Under this condition, cavitation is induced by suction of air bubble into tracheal elements through the pits in the cell wall of plant (Hacke *et al.*, 2001). Jackson *et al.* (1996) reported that cavitation of water columns within the xylem of plant could be detected using acoustic emission method, and this method was useful to determine the threshold water potential at which the plant damage was initiated. Observation of AE signals from plant and plant transpiration system in tomato was performed by Qiu G.Y. *et al.* (2002). It was found that AE signals, under mild or absence of water stress conditions, increased with the increase of plant transpiration rate statistically, and AE signals tended to be affected by the change of transpiration system depending on the water stress levels. The relation between ultrasonic acoustic emission and stem diameter was discussed by Holtta T. et al (2005). They discovered that measured AE signals coincided well with changes of xylem diameter, and AE signals highly occurred during periods of decreasing stem xylem diameter, i.e., increasing water tension. Jia X. *et al.* (2006) studied on AE signals from leaf xylem of potted wheat subject to a soil drought. These results revealed that very few AEs occurred in well-watered plant, whereas great amounts of AEs were detected during the drought cycle. The correlation of sap flow in trees and acoustic emission signals were discussed by Černý M. *et al.* (2011) and Mazal P. *et al.* (2012). They confirmed that detected AE signals from trees reflected embolic event in vessels occuring during rapid changes in sap flow rate. However, Lasckimke *et al.* (2003) proposed that acoustic emission from plants did not necessarily cause from water stress condition. AE signals might be generated by unknown hydraulic events being more complex than cavitation. Thus, new results of AE signals from transpiring plants was presented by Lasckimke *et al.* (2006) that the abrupt regrouping of the wall adherent bubble system was the origin of acoustic emission from plants, and the frequency spectrum and the waveforms of the detected acoustic emissions contradicted the traditional assumptions according to acoustic emission caused by cavitation disruption of the stressed water column. From aforementioned publications, utilizing AE method as NDT technique in agriculture, particularly in monitoring the drought stress of plant, is likely to be newly innovative technology for recognizing the plant condition responding to different environments. Therefore, the objective of present study was to justify the characteristics of detected AE signals from investigated plants under controllable environment in order to find more information of using AE signals for indicating the water stress condition on plant. To more understand, multiple regression analysis was presented to describe the correlation between environmental parameters and AE signals generated from test plants over experimental period as well.

MATERIALS AND METHODS

Plant preparation

Providing the investigated plant and experimental set-up were completely conducted at Department of Technology and Automobile Transport, and Department of Plant Biology, Faculty of Agronomy, Mendel University in Brno. This study was performed at 9.30 AM from March 27^{th}–April 3^{rd}. Two specimens of maize, which was a variety of Piorun, were chosen to be used in experiment as experimental sample. The investigated maize were planted in February 9^{th}, 2015 by sowing in plot. This plot had dimensions 20 cm in height and 25 cm in diameter with substrate (Klasmann TS30), which had the size of substance about 0–5 mm. Before implementing experiment, all investigated plants were watered by clean water of 500 cc, and then the top part of all pots was neatly covered by



1: *Acoustic emission system utilized in experiment*
(a) AE acquisition device (b) broadband AE sensor with metal waveguide (c) AE preamplifier
(d) Environmental monitoring sensor (EMS)

using aluminium foil sheet in order to prevent the evaporation of water from soil surface to outside environment during experiment.

Acoustic emission monitoring

Implemented AE instrumentation in this experiment as shown in Fig. 1 (Dakel Corp, Czech Republic) consisted of a transducer connected with metal waveguide, a pre-amplifer, an environmental monitoring sensor (EMS), and an acquisition device. The transducer was a broadband IDK-09 type (piezoelectric disk) from Dakel Corp. It has been selected because of its operating frequency of 25–60 kHz. To magnify AE signals, the AE preamplifier of 35 dB was used to improve the detected AE signals before converted from analog signals to digital signals by AE acquisition system. The acquisition system was completely computer controlled. The waveforms and the classical acoustic parameters (events number, amplitude, risetime, counts number, etc.) were stored on a hard disk as soon as detected, and also EMS would simultaneously record the environmental parameters data such as air temperature, relative humidity, air pressure, and light intensity. Both AE and environmental data were analyzed and shown the outcome by Daemon and Deashow which were the specific software developed by Dakel Corp (Czech Republic).

Experimental procedures

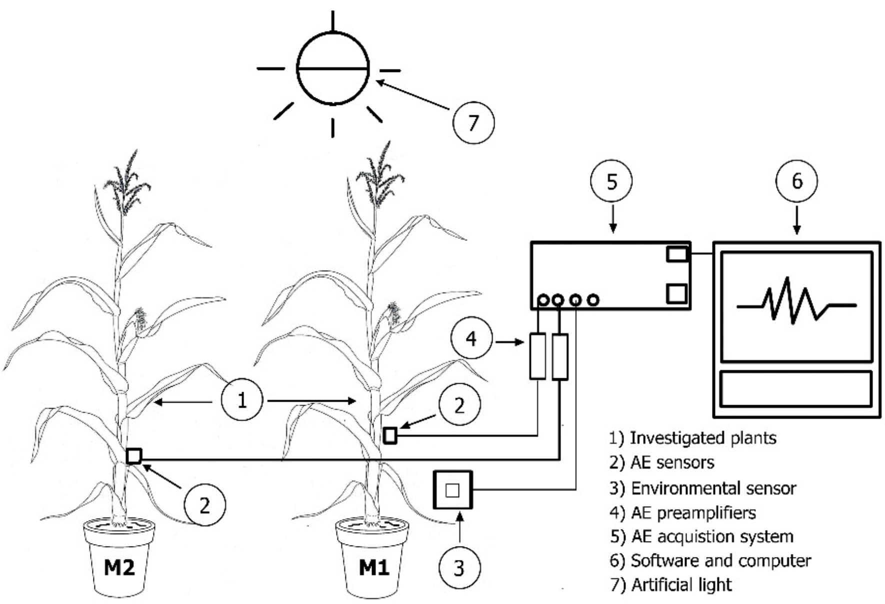
In the experiment, two samples of maize were, concurrently, monitored by AE method within controllable environment as illustrated in Fig. 2. Firstly, in order to make different condition in each maize, one maize (M1) was placed on table closer to the artificial light than another one (M2) was. Afterward, Mounting AE sensors on the investigated maize were done by putting each AE sensor at middle position of internode of plant in which AE sensor was put away from soil surface around 15 cm. Then, the experiment was carried out for a week. Recognizing the water stress condition in plant during experiment was noticed by seeing the external appearance of plant and recorded it on paper to compare with AE signal results from the computer software later. Lastly, to avoid the server water stress condition happening on investigated plant in any cases, when the investigated plant was wilting, or under water stress condition, it would be watered immediately.

Statistical analysis

To study the correlation between variation of detected AE signals from investigated plant and change of environmental parameter values, multiple regression analysis was performed to explain environmental parameters of which were the most important to affect to the value of AE signals. In statistics, multiple regression analysis is a methodology for evaluating a functional relationship among dependent variables and independent variables. In this study, we used multiple regression analysis by defining root mean square value (RMS) of AE signal as a dependent variable, and environmental parameters as the independent variables.

Multiple linear regression

Multiple regression analysis is a powerful technique used for predicting the unknown value of a variable from the known value of more variables



2: *Setting up AE equipment with investigated maize* (predictors). In general, the multiple regression equation of Y on $X_1, X_2, \ldots, X_k$ is given by (The MINITAB, 2016):

$$Y = {}^{2}{}_{0} + {}^{2}{}_{1}X_1 + {}^{2}{}_{2}X_2 + \cdots + {}^{2}{}_{k}X_k + \mu \quad (1)$$

Here Y is the dependent variable, and $X_1, X_2, \ldots, X_k$ are the independent variables and $\beta_0, \beta_1, \ldots, \beta_k$ are analogous to the slop in linear regression equation, and also called regression coefficients. ε is an error to account for the discrepancy between predicted data and the observed data. The predicted value form of Eq. (1) is written by:

$$\hat{Y} = \hat{\beta}_0 + \hat{\beta}_1 X_1 + \hat{\beta}_2 X_2 + \cdots + \hat{\beta}_p X_p \quad (2)$$

Here $\hat{Y}$ is the predicted value and $\hat{\beta}_1, \hat{\beta}_2, \cdots \hat{\beta}_p$ are estimates of the regression coefficients.

Once a multiple regression equation was calculated. The coefficient of determination (R^2) can be used to check how close the data fit this regression line. R^2 as shown in Eq. (3) always lies between 0 and 1.

$$R^2 = 1 - \frac{\Sigma(y_i - \hat{y}_i)^2}{\Sigma(y_i - \overline{y}_i)^2} \quad (3)$$

Here $\Sigma(y_i - \hat{y}_i)^2$ and $\Sigma(y_i - \overline{y}_i)^2$ are called sum of squared errors (SSE) and total sum of squares (SST), correspondingly.

The value of R^2 varies between 0 and 1; a value of $R^2 = 0.9$ indicates that 90 % of the total variability in the response variable is accounted for by the predictor variables. However, a large value of R^2 does not necessarily mean that the model fits the data well. Thus, a more detailed analysis is needed to ensure that the model can satisfactorily be used to describe the observed data and predict the response for another set of data different from the one used to generate the model. The value used to check the regression model other than R^2 is adjusted R^2 (STATISTICS HOW TO, 2016) as shown in Eq. (4).

$$R^2_{adj} = 1 - \left[\frac{(1-R^2)(n-1)}{(n-k-1)}\right] \quad (4)$$

Here n is the number of points in data sample, k is the number of variables in model.

RESULTS

The experiment of detecting AE characteristics of plants due to water stress condition was continuously implemented for seven days. From observation of test plants during experiment, it was found that maize (M1) started wilting on the fifth day of experiment. In order to avoid M1 being serve water stress, M1 was watered by 500 cc of clean water. After two hours of re-watering, M1 obviously became well condition without wilting appearance. On other hand, investigated maize (M2) did not appear to be water stress condition throughout the entire experimental period. After conducting the experiment, the AE signal outcomes of the experiment can be presented by line graphs in Fig. 3. The values of AE parameters (RMS and counts number) detected from both plants and air temperature, light intensity and relative humidity versus time were illustrated by Fig. 3 (a, b, c, d, e, f). According to these graphs, both M1 and M2 evidently generated a large number of AE signals during daytime, but a small number of AE signals were detected during night time. However, M1 showed very strong variation of AE signals during night and day time from fourth to fifth day of experiment when it was appeared to be wilting condition by itself as results displayed in Fig. 3(a, b, c). On the contrary, M2 did not present such the strong variation of AE signals during night and day as illustrated in Fig. 3 (d, e, f). Moreover, it was interesting that the characteristics of AE signals of M1 were likely to be weaker signals after M1 was re-watered, particularly in counts number, and the features of AE signals detected from M2 over the experimental time was more obvious than that of M1 was, especially in RMS signal.

Fig. 3 Detected AE parameter values of maize (M1) and environment parameters versus time (a, b, c), detected AE parameter values of maize (M2) and environment parameters versus time (e, f, g)

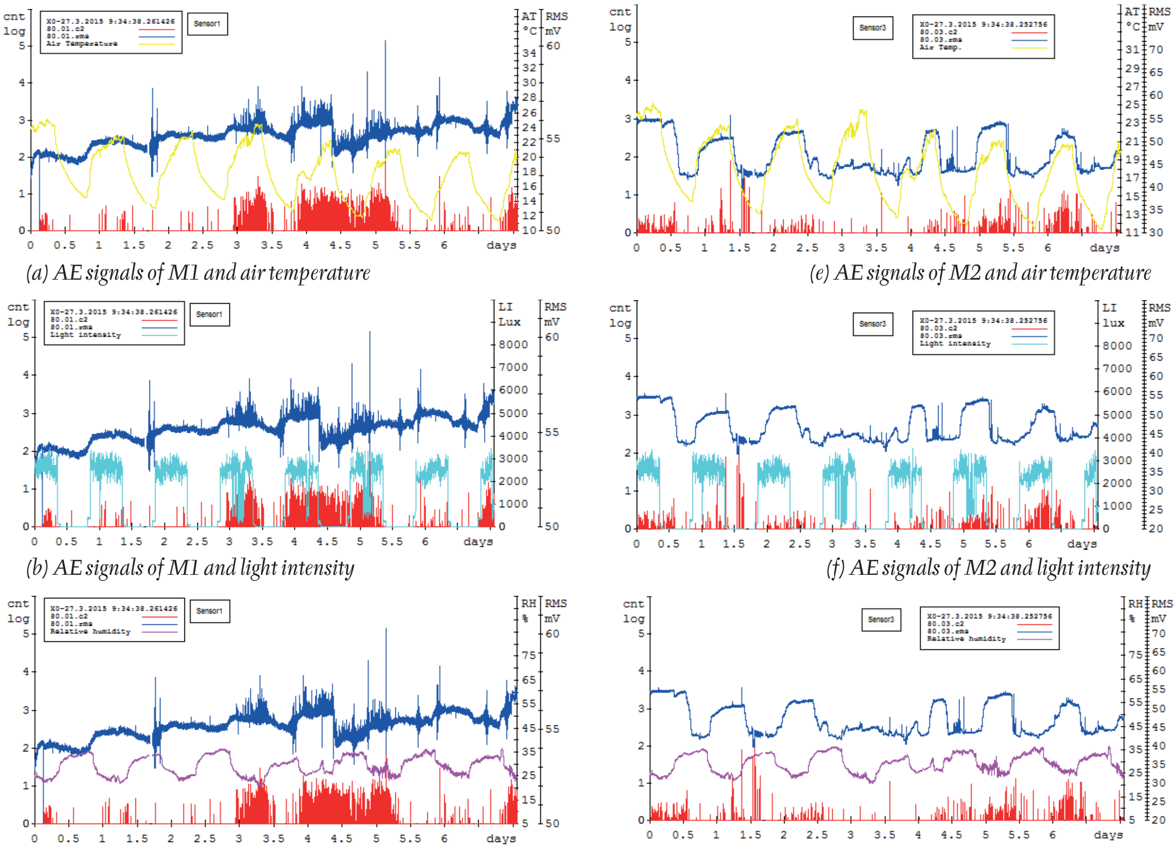
Multiple regression was determined to find the statistical relationship between dependent variable, which is detected RMS value of M1 and M2 specimens, and independent variables, which are air temperature (AT), light intensity (LI), relative humidity (RH), and air pressure as written by Eq.(5).

$$RMS = Y + a.AT + b.LH + c.RH + d.AP \quad (5)$$

Where:
Y = Y interception
a = Regression coefficient of AT
b = Regression coefficient of LH
c = Regression coefficient of RH
d = Regression coefficient of AP

In Tabs. I, II list the regression coefficients and quality indicators of regression analysis of M1 and M2 in each experimental day, after calculated by Eq. (5).

Fig. 4 present a line graph that comparing the R^2 of multiple regression of M1 and M2. From Fig. 4, all R^2 values of M2 were higher than all R^2 values of M1 throughout experimental period. The R^2 of M1 were equal to 76.0, 77.0, 62.2, 51.3, 80.5, 41.6, and 82.5 %, and the R^2 of M2 were equal to 83.0, 90.4, 92.8, 65.3, 82.9, 88.4, and 84.7 % from first day to seventh day of experiment, respectively. The R^2 values of M1 and M2 similarly started decreasing their values from third to fourth experimental day, because detecting AE signals from plants of AE sensors was not effective at the same position after



(a) AE signals of M1 and air temperature

(e) AE signals of M2 and air temperature

(b) AE signals of M1 and light intensity

(f) AE signals of M2 and light intensity

(c) AE signals of M1 and relative humidity

(g) AE signals of M2 and relative humidity

3: *Setting up AE equipment with investigated maize*

I: *Multiple regression analysis of M1 in experiment throughout seven days*

Day	Regression coefficients					Regression quality indicators		
	Y	a	b	c	d	S	R^2	Ad R^2
1	-134.12	0.0408	0.0001	0.0154	0.1834	0.1597	76.0 %	75.7 %
2	113.951	0.066	0	-0.0076	-0.0591	0.0961	77.0 %	76.3 %
3	78.337	0.0074	0.0001	-0.0021	-0.0233	0.112	60.2 %	59.1 %
4	72.089	0.0079	0.0001	0.0108	-0.0172	0.1717	51.3 %	49.9 %
5	114.62	0.0132	0.0003	-0.0118	-0.0597	0.2693	80.5 %	79.9 %
6	-22.98	-0.0553	0.0002	0.0068	0.0779	0.2086	41.6 %	39.9 %
7	28.704	0.083	0.0002	0.0432	0.0239	0.1308	82.5 %	82.0 %

II: *Multiple regression analysis of M2 in experiment throughout seven days*

Day	Regression coefficients					Regression quality indicators		
	C	a	b	c	d	S	R^2	Ad R^2
1	-130.4	2.1779	-0.0027	0.2575	0.1305	2.1280	83.5 %	83.0 %
2	34.25	0.6312	-0.001	-0.5265	0.0167	1.0707	90.7 %	90.4 %
3	-345.55	0.8044	-0.0018	-0.2027	0.3847	1.0383	93.0 %	92.8 %
4	123.38	-0.195	0	-0.3949	-0.0649	0.6271	66.3 %	65.3 %
5	-539.01	1.965	-0.0005	0.7462	0.5299	1.4785	83.4 %	82.9 %
6	568.4	1.4151	-0.0004	-0.001	-0.5369	1.6404	88.8 %	88.4 %
7	319.62	0.436	0	-0.2502	-0.2695	1.2233	85.1 %	84.7 %

S = Standard error
R^2 = Coefficient of determination
Ad R^2 = Adjusted R^2

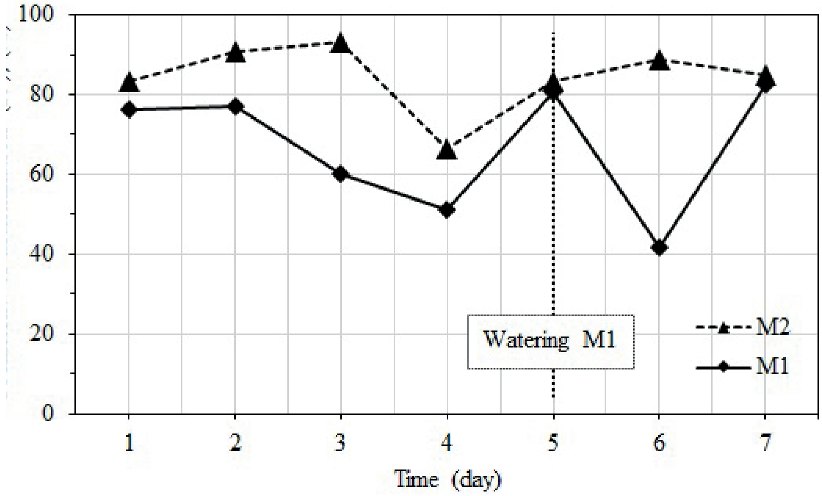
three days, so theses AE sensors were moved to new vicious position. Afterward, the R^2 value of M1 and M2 alike increased again at fifth experimental day. Furthermore, it was noticed that the R^2 value of M1 dramatically decreased after M1 was re-watered at the beginning of sixth experimental day.

DISCUSSION

In this experiment, M1 was positioned closer artificial light than M2, and this might be the main reason that M1 was under water stress condition at fifth day of experiment by observing its external appearance, whereas M2 did not show its water stress condition throughout experimental period. From Fig.3 (a, b, c), M1 generated a large number of AE signals during night and day time at fifth day of experiment, and then detected AE signals from M1 became a small number of AE signals after two hours of re-watering M1. From this situation, we supposed these detected AE signals were established from cavitation event in xylem on plant exposed to severe soil water deficit. This result is consistent with the other publications (Jia *et al.*, 2006 and Černý *et al.*, 2011) which reported that AE signal occurrence in water stressed plant remained higher than that of in well-watered plant because of soil dehydrated. For detecting AE signals of M1 and M2 by AE sensors, it was found that recieving AE signals of AE sensor in M2 was better that that of AE sensor in M1. This possibly indicated that considering the area in which AE sensor was placed on test plant was very important to affect to the performance of AE sensore detecting signals from plant, and also the shape of waveguide that was coupled with AE sensor should be designed to recieve the AE signals from test plant effectively and consistently. According to statistical analysis, the results of multiple regression equation of M1 and M2 presented that air temperature factor was the most significant parameter, and the light intensity factor was the least parameter influencing to the change of RMS value in M1 and M2 plants. For R^2 values as can be seen in Fig.4, all R^2 values of M2 were higher than all R^2 value of M1. This might be because detecting AE signals of AE sensor for M2 was more effective than that of AE sensor for M1. Moreover, R^2 value of M1 was immediately decreased after re-watering M1 at fifth experimental day. This situation was supposed that the cavitation event in xylem of M1 decreased after re-watering, and this also affects to the RMS value of M1 decreasing, because RMS directly varies in the number of cavitation event. When RMS decreased, R^2 became lower value than usual. Therefore, when R^2 have a high value, it can indicate that strong cavitation event occur in xylem of plant, and if there is no water enough for plant, plan will show the condition of water stress then. On the other hand, when R^2 have a low value, it can indicate that there might be no or small cavitation event happening in the xylem of plant.

CONCLUSION

Studying AE signal characteristics generated from investigated plants was implemented in this experiment. The experimental results indicated that responsibility of plant due to its water stress level could be acquired by AE technique. In this experiment, it was found that investigated plants would produce a large number of AE signals during daytime, and even generate a very larger number of AE signals when the investigated plant was under water stress condition. From this situation, we supposed the occurrence of these AE signals might relate to cavitation event in plant due to its transpiration system. In accordance with calculating multiple regression equation, this results shown that the change of AE signal value detected from



4: *Comparison of the coefficients of determination of multiple regression of M1 and M2.*

investigated plant was mostly and least affected by air temperature and light intensity value, respectively, and also Coefficient of determination (R^2) could be used to describe the state of water stress condition in plant. Therefore, monitoring plant transpiration system using AE method is proposed to be a great promise for process understanding, and potential recognizable system on water stress of plant.

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