doi: 10.17221/691/2016-PSE

Impact of heat and drought stresses on size and quality of the potato yield

Krystyna RYKACZEWSKA

Plant Breeding and Acclimatization Institute – National Research Institute, Department of Potato Agronomy, Research Centre in Jadwisin, Serock, Poland

**Corresponding author: k.rykaczewska@ihar.edu.pl*

ABSTRACT

Rykaczewska K. (2017): Impact of heat and drought stresses on size and quality of the potato yield. Plant Soil Environ., 63: 40–46.

Potato (*Solanum tuberosum* L.) is a plant typical mainly for temperate climate and develops best at about 20°C. Heat stress due to increased temperatures is an agricultural problem in many areas in the world. The aim of our work was to assess the response of selected new potato cultivars to heat and drought stress during the subsequent stages of plant growth starting from buds forming. The pot experiment was carried out over the course of two years with the following early cultivars: Lord, Miłek, Gwiazda, Hubal, Oberon and Tetyda. The impact of heat (38°C/25°C) and drought stress on potato plants was tested in four periods of two weeks. In these periods half of the plants were watered to a level close to optimal while the other half remained without irrigation. Our studies demonstrated that tested potato cultivars' response to heat stress depends on the growth stage, in which the temperature acts on the plants and on the soil moisture. Besides the decrease in yield and tubers' diminution, the biggest problem was the presence of tubers with physiological defects, particularly of immature tubers. The response of cultivars was differentiated.

Keywords: global warming; period of high temperature; reduction in economic potato yield; second tuberization; chlorophyll *a* fluorescence

According to a report of the Intergovernmental Panel on Climatic Change assessment of many studies covering a wide range of regions and crops, that negative impacts of climate change on crop yields have been more common than positive impacts (IPCC 2014). Forecasts of global warming and periods of high temperature and drought becoming more frequent prompt scientists to study the response of crops to heat.

Heat stress is defined as 'the rise in temperature beyond a threshold level for a period of time sufficient to cause irreversible damage to plant growth and development (Wahid et al. 2007). Generally a transient elevation in temperature, usually 10–15°C above ambient, is considered to be the heat stress. Temperature is one of the most important uncontrollable factors affecting crop yield and heat stress is an agricultural problem in many areas in the world (Birch et al. 2012). According to Wahid et al. (2007) 'transitory' or constantly high temperatures cause an array of morpho-anatomical, physiological and biochemical changes in plants, which affects plant growth and development and may lead to a drastic reduction in economic yield'.

Potato (*Solanum tuberosum* L.) is a plant typical mainly for temperate climate. The limits and optimal values for the growth of the aboveground part of the potato plant and for the tubers are different (Van Dam et al. 1996). Under high-temperature conditions, tuberization is significantly inhibited and photoassimilate partitioning to tubers is greatly reduced (Lafta and Lorenzen 1995). According to Wahid et al. (2007) the adverse effects of heat

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Table 1. Mean values of air temperature and photosynthetically active radiation (PAR) during growing season in the years of study

Meteorological factor	Year	Month				Mean
		May	June	July	August	
Temperature (°C)	2014	14.1	15.8	21.4	18.3	17.4[a]
	2015	12.9	17.5	19.7	22.5	18.2[a]
PAR (J/m/s)	2014	339	322	346	335	335[a]
	2015	308	399	365	409	370[a]

[a,b]mean values followed by the same letters are not significantly different at the 0.05 level according to the Tukey's test

stress can be mitigated by developing crop plants with improved thermotolerance using various genetic approaches. For this reason, a thorough understanding of physiological responses of potato plants to high temperature is imperative (Veilleux et al. 1997, Levy and Veilleux 2007).

The aim of this work was to assess the response of selected new potato cultivars to heat stress during the subsequent stages of plant growth in time of the growing period, under soil moisture conditions favourable to plants and under drought conditions.

MATERIAL AND METHODS

The pot experiment was carried out in open area next to a greenhouse and in a growth chamber, over the course of two years 2014–2015. The following early cultivars were tested: Lord, Miłek, Gwiazda, Hubal, Oberon, Tetyda. The impact of high temperature day/night 38°C/25°C on potato plants was tested in four periods: I – May 15–30; II – June 1–15; III – June 16–30; IV – July 1–15. In these periods half of the plants were watered to a level close to optimal (favourable soil moisture), while the other half remained without irrigation (soil drought). The control combination consisted of potato plants grown throughout the whole season under conditions close to optimal.

Weather conditions during the years of study were monitored using a Campbell Weather Station (Campbell Scientific Inc., USA) located adjacent to the greenhouse and additionally using a thermohygrograph placed between pots. The two most important meteorological factors, air temperature and the photosynthetically active radiation, are presented in Table 1.

Minitubers were pre-sprouted for 5 weeks and next used for planting. They were planted in 10-L pots filled with a thin layer of gravel and soilm which is the standard substrate for vegetables, enriched by a fertilizer Osmoform Permanent (Everris) at the recommended dose. The number of objects (pots) totalled 234, and each cultivar accounted for 39. Date of planting was April 15 in both years. The pots with plants were set outdoors, adjacent to the greenhouse. The density of pots was 4 per m^2. Throughout the growing season the plants were carefully tended daily and regularly watered at a level close to optimum. Recommended plant protection products were used to control diseases and pests. Phenological stages of plants in subsequent periods of the growing season are presented in Table 2. Just before the impact of heat and drought stress plant characteristics were determined. Leaf surface was measured using a Leaf Area Meter 3100 (Campbell Scientific Inc., USA). Chlorophyll *a* fluorescence measurements were performed on the plants with a Pocket PEA (Plant Efficiency Analyzer, Hansatech, UK). Determined parameters were: PI – performance index of photosystem II (PS II) in relative units and F_v/F_m – the ratio of variable to maximal chlorophyll *a* fluorescence (the photochemical efficiency of photosystem II). Just before the start of the heat treatment, six plants of each cultivar were transferred to a growth chamber for a period of 14 days. Conditions in the growth chamber were: photoperiod 15 h, lighting with Philips SON-T Agro 400W lamps (100–120 W/m^2

Table 2. Stages of plant development just before the impact of heat and drought stress in subsequent periods of growing season – mean values for tested cultivars and years

Period of stress	Days after planting	Phenological stage
I	33–46	buds forming
II	46–61	flowering
III	61–75	development of fruits
IV	75–89	beginning of maturity

doi: 10.17221/691/2016-PSE

Table 3. Plant characteristics just before the impact of heat and drought stress in subsequent periods of growing season – mean values for tested cultivars and years

Period of stress	Plant height (cm)	LAI	PI	F_v/F_m	Tuber weight per plant (g)
I	32.2[c]	1.40[c]	9.68[a]	0.84[a]	1[d]
II	59.9[b]	3.37[b]	7.94[b]	0.85[a]	140[c]
III	77.8[a]	4.26[a]	4.08[c]	0.83[a]	609[b]
IV	76.5[a]	4.48[a]	2.51[d]	0.80[b]	1233[a]

[a,b,c,d]mean values followed by the same letters are not significantly different at the 0.05 level according to the Tukey's test. LAI – leaf area index; PI – performance index; F_v/F_m – the ratio of variable to maximal chlorophyll *a* fluorescence

at 1.5 m). The temperature was maintained at a level established by experiment (38°C/25°C). Half of the plants were watered regularly to a level close to the optimum (favourable soil moisture) and the other half were subjected to soil drought by ceasing watering (soil drought). After the end of heat stress periods, measurements of plant height and chlorophyll *a* fluorescence were performed again. Then plants were moved outdoors where further development under conditions close to optimal took place.

Final harvest was performed after full maturity of plants in the control combination, between July 28 and August 11. The size of the assimilation area of plants in other combinations was measured. The total mass and number of tubers, larger and smaller than 3 cm of transversal diameter per plant were determined. The size of individual tubers was calculated. The presence of physiological defects in the tubers, mainly deformations, gemmations, sprouting and immature tubers (physiologically younger)

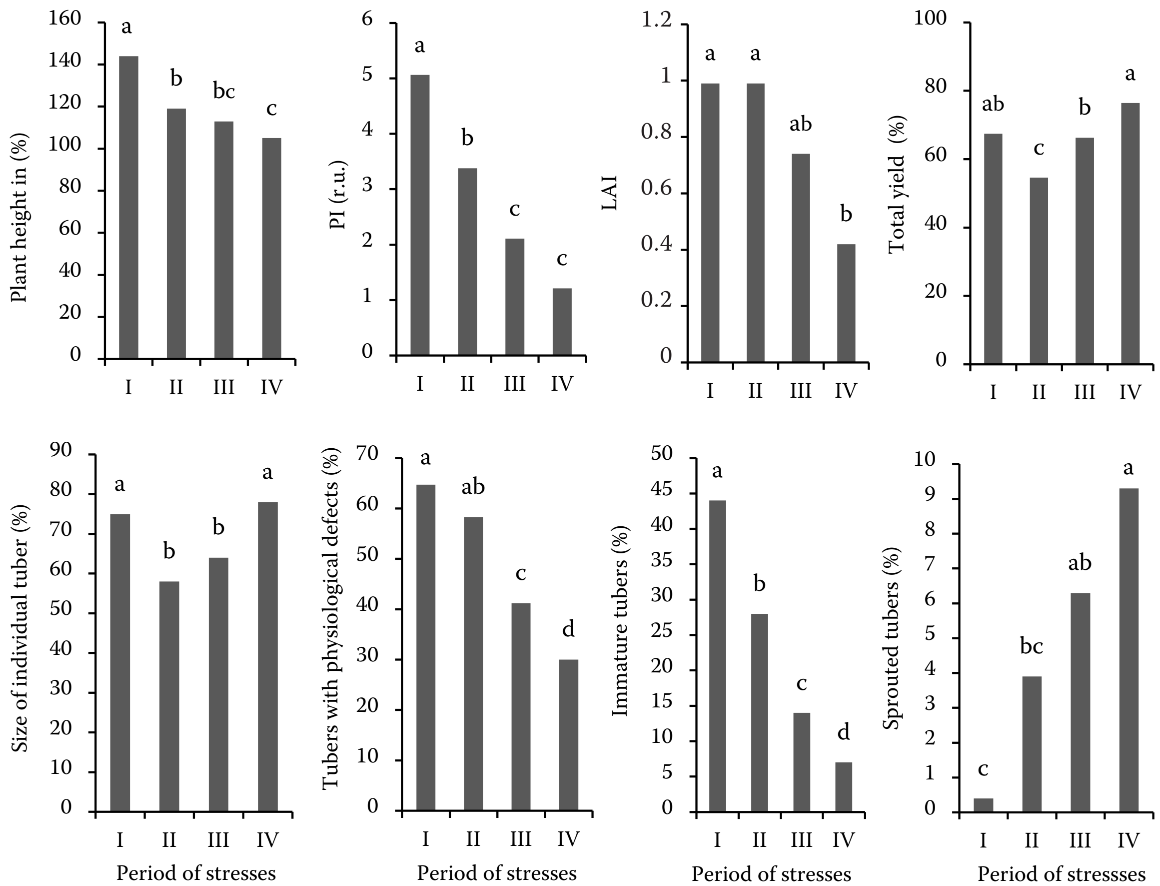

Figure 1. The impact of short period of high temperature and drought stress on the plant and yield characteristics – mean values for soil moisture and cultivars – in relation to the control. LAI – leaf area index; PI – performance index

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were determined as a percentage of the total yield of tubers.

The results of the experiments were analysed using ANOVA with Statistica 12 computer programme. Means were separated with Tukey's contrast analysis at the significance level 0.05.

RESULTS AND DISCUSSION

Plant characteristics just before the impact of heat and drought stresses. Height of plants, leaf area index and tuber weight increased with the physiological age of plants (Table 3). However, the values of chlorophyll *a* fluorescence parameter PI decreased. This is consistent with previous research findings of Rykaczewska and Mańkowski (2015). High values of F_v/F_m, above 0.80 indicate a good physiological state of plants in the experiment.

Height of plants and chlorophyll *a* fluorescence parameter PI immediately after the impact of heat and drought stresses. In the first periods of heat stress cultivars responded with an increase in height (Figure 1). The reaction of plants under conditions of increasing drought was significantly weaker (Figure 2). The results are consistent with the results of previous studies whereby a temperature higher than optimal intensified development of the aboveground part of plants (Rykaczewska 2013b, 2015). Heat stress under drought conditions negatively influenced PI activity in the tested plants. In literature, there is little information on the fluorescence of chlorophyll *a* in leaves of potato plants, especially in the context of the comparison of cultivars' response to heat stress impact (Rykaczewska and Mańkowski 2015).

Final yield. Final yield of the tested cultivars in the control was relatively high (Table 4). There were normal differences between cultivars, which are the result of their ability to yielding and physiological seed vigour in given environment (Rykaczewska 2013a).

At the final harvest performed after full maturity of plants in the control combination, the plants subjected to heat were partially immature, which was the result of secondary growth. The size of the assimilation area of plants depended on the period of heat stress and the soil moisture (Table 5, Figures 1 and 2). Secondary growth of the above ground part of plants was associated with second-

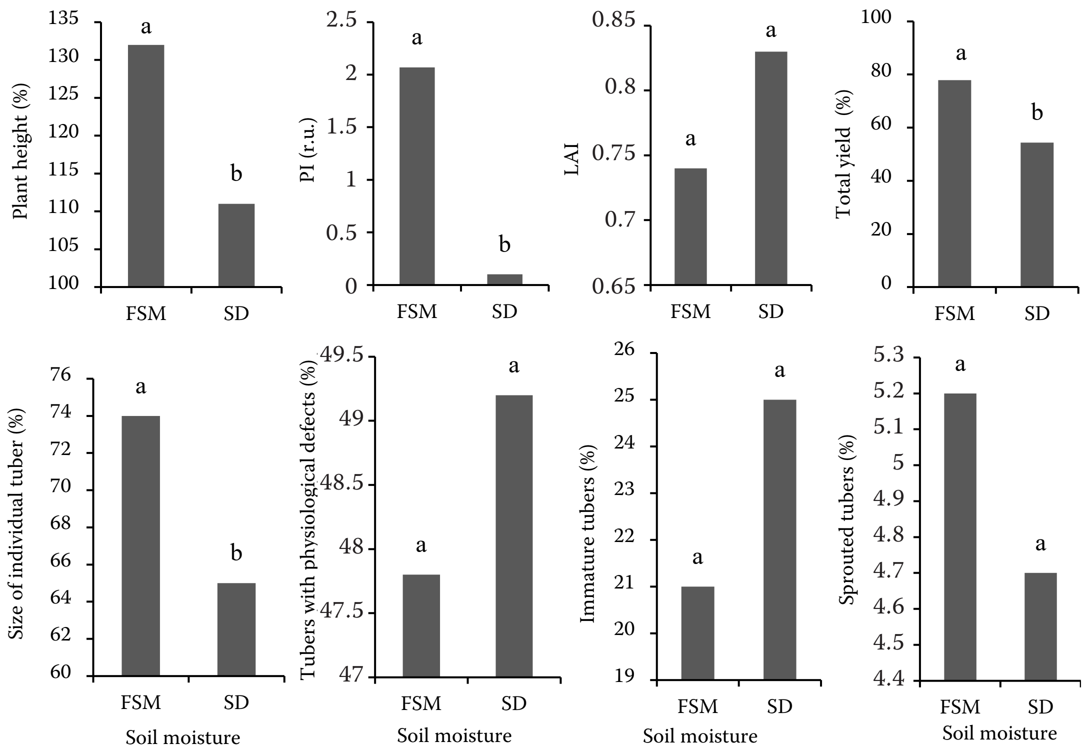

Figure 2. The impact of short period of heat stress on the plant and yield characteristics depending on soil moisture – mean values for cultivars and particular periods – in relation to the control. LAI – leaf area index; PI – performance index

doi: 10.17221/691/2016-PSE

Table 4. Characteristics of final yield in the control

Cultivar	Yield/plant (g)	Number of tubers > 3 cm /plant
Lord	2268^{a}	25.0^{ab}
Miłek	1743^{b}	16.0^{b}
Gwiazda	2064^{ab}	24.5^{ab}
Hubal	1727^{b}	22.0^{b}
Oberon	2084^{ab}	34.0^{a}
Tetyda	2225^{a}	24.0^{ab}
Mean	2019	24.2
2014	2037^{a}	22.3^{b}
2015	2000^{a}	26.2^{a}

^{a,b,c}mean values followed by the same letters are not significantly different at the 0.05 level according to the Tukey's test

ary tuberization. The number of tubers of 1–3 cm increased significantly under the influence of heat stress independent of the soil moisture level. Similarly, the experiment conducted by Bodlaender et al. (1964) showed that high temperature induces second-growth in potato tubers irrespective of the water supply and that drought is not necessary to induce the second-growth.

The heat stress during the growing season had a negative effect on the final yield of the tested cultivars (Figures 1–3). The effect was strongest when the heat stress influenced plants in the II period. When the time of heat stress treatment on potato plants was delayed the negative effect on the yield of tubers became weaker. There were no statistically significant differences between cultivars, which indicates a generalized effect. In the study of Levy (1986) heat stress reduced tuber yields of ten tested potato genotypes from zero to 96 percent but the experiment was conducted under natural conditions in a semi-arid environment and a comparison was made between two cycles of vegetation.

The number of tubers with transversal diameter above 3 cm in the final yield was significantly dependent on the soil moisture during the impact of heat and cultivar (Table 5). A significant increase in the number of tubers under influence of heat stresses acting in the second, third and fourth period in conditions of favourable soil moisture was found. An increase in the number of tubers as a result of high temperature stress was also found in the earlier study (Rykaczewska 2015). A similar phenomenon was observed by Levy (1986).

Heat and drought stress reduces the size of individual tubers. In the study presented here, a highly significant effect of the period of stress and cultivar on the tuber size in the yield was found (Figures 1–3). The greatest diminution of tubers under the influence of heat and drought stress occurred in the second and third periods, i.e. at the time of plant flowering and development of fruits.

Tuber physiological defects. High temperature acting in subsequent stages of plant development had a negative effect on tuber physiological defects: deformations, gemmations, tubers sprouting in the soil before harvest and tubers physiologially younger (immature) (Table 7, Figures 1–3). The sum of tubers with physiological defects as a percent of the total yield shows a significant dependence on the period in which the stress affected plants and different reactions of cultivars. The strongest was the impact of stress on the plant in the first period. Among the tested cultivars, the smallest

Table 5. Leaf area index (LAI) at the time of harvest and tuber number in the final yield in relation to the control depending on soil moisture and period of heat stress (HS) – mean values for cultivars

Soil moisture	Period of HS	LAI	Tuber number in relation to the control (%)	
			tuber 1–3 cm	tuber > 3 cm
Favourable soil moisture	I	0.75	152	93
	II	0.74	240	122
	III	0.84	220	116
	IV	0.63	247	112
Soil drought	I	1.23	259	96
	II	1.24	258	71
	III	0.64	230	91
	IV	0.21	112	83
$HSD_{0.05}$		0.40	45	23

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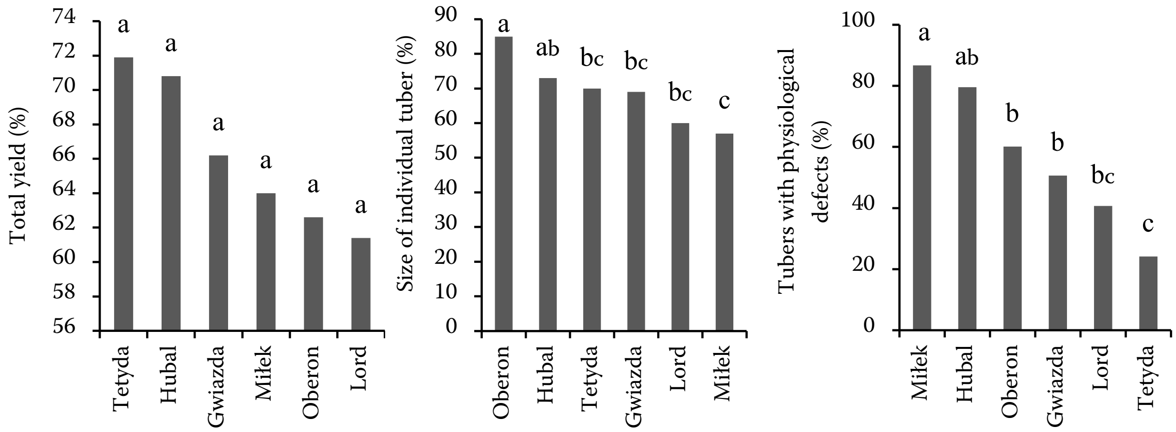

Figure 3. The impact of short period of high temperature and drought stress on yield characteristics of the tested cultivars – mean values for periods and soil moisture – in relation to the control

number of tubers with physiological defects was found in cv. Tetyda.

Our study shows that the percentage of deformed tubers and tubers chronologically younger in the yield was the largest problem. In the case of tubers' deformation, the largest share of these tubers in the final yield occurred when heat stress was applied in the period II, during plant flowering. However, Levy (1986) stated that a single treatment of high temperatures during early stages of tuber development caused a lower percentage of misshapen tubers. This indicates that studies of this phenomenon require a larger number of cultivars and a more precise determination of the plant development stage at the beginning of the impact of heat stress.

Although the percentage of tubers sprouted before harvest was generally low, it was more important if heat stress was applied in the fourth period, at the beginning of plant maturity (Figure 1).

The significant correlation between investigated traits of plants and some tuber physiological defects influenced by heat stress in subsequent stages of plant development confirms the negative, very

Table 6. The impact of heat and drought stress on physiological tubers defects (% of total yield) – depending on tested factors

Tested factor		Deformations	Gemmation	Sprouted	Physiologically younger
Soil moisture	FSM	17.0^{a}	4.2^{a}	5.2^{a}	21.4^{a}
	SD	16.3^{a}	2.8^{a}	4.7^{a}	25.4^{a}
Period of HS	I	17.5^{ab}	2.7^{a}	0.4^{c}	44.1^{a}
	II	21.6^{a}	4.5^{a}	3.9^{bc}	28.3^{b}
	III	17.4^{ab}	3.5^{a}	6.3^{ab}	14.0^{bc}
	IV	10.2^{b}	3.4^{a}	9.3^{a}	7.1^{c}
Cultivar	Lord	12.2^{b}	7.0^{a}	9.1^{a}	12.4^{b}
	Miłek	16.4^{b}	4.1^{abc}	5.2^{ab}	20.3^{b}
	Gwiazda	10.3^{b}	5.8^{ab}	7.4^{a}	27.1^{ab}
	Hubal	35.2^{a}	1.4^{bc}	0.4^{b}	42.6^{a}
	Oberon	18.1^{b}	2.1^{bc}	3.5^{ab}	26.4^{ab}
	Tetyda	7.9^{b}	0.5^{c}	4.1^{ab}	11.6^{b}
Year	2014	14.2^{b}	3.2^{a}	5.1^{a}	30.7^{a}
	2015	19.2^{a}	3.7^{a}	4.8^{a}	16.1^{b}

FSM – favourable soil moisture; SD – soil drought; HS – heat stress; a, b, c – mean values followed by the same letters are not significantly different at the 0.05 level according to the Tukey's test

doi: 10.17221/691/2016-PSE

Table 7. Correlation coefficients between traits of plants and tubers with physiological defects influenced by heat stress in subsequent stages of plant development – independently on the level of soil moisture

Correlation	Coefficient
Relative height of plants × tubers sprouted (%)	–0.9419**
Relative height of plants × tubers physiologically younger (%)	+0.9555**
Relative height of plants × total tubers defects	+0.8551**
PI × tubers sprouted (%)	–0.9996**
PI × tubers physiologically younger (%)	+0.9906**
PI × total tubers defects	+0.9694**

PI – performance index; ** $P < 0.01$

strong effect of heat stress during the growing season on plants and tuber physiological defects in total yield of the tested cultivars (Table 7).

In conclusion, our studies on the impact of heat and drought stress on size and quality of the potato yield show that the total yield is not the only indicator of potato tolerance to high temperatures during the growing season, but the assessment should also take into account the occurrence of secondary tuberization and physiological defects of tubers. The indication of tolerant cultivars allows their selection for cultivation in region with higher temperatures and allow their use in breeding of new genotypes. The progress of genomics and bioinformatics offers real opportunities for the genetic improvement and can entail development of cultivars tolerant to environmental stresses.

Acknowledgements

The author offers special thanks for the valuable technical assistance of A. Gajos during the whole period of growing season.

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Accepted on October 24, 2016
Received on December 14, 2016