Corrugating Medium Made from Solid Waste of Bamboo Paper Sludge

Mei-Ling Chen,[a,b] Chuan-Gui Wang,[b,]* Ben-Hua Fei,[a,]* Heng Wu,[b] and Shuang-Yan Zhang [b]

Corrugating medium was made from the solid waste of bamboo paper sludge and old corrugated container (OCC) pulp. The medium also incorporated additions of anion polyacrylamide as a retention agent and cationic starch as a strengthening agent. The estimated molecular mass of anion polyacrylamide, the addition level of anionic polyacrylamide, and the addition level of cationic starch were optimally designed using single-factor analysis. On this premise, the optimum addition level of the solid waste of bamboo paper sludge was found. The best process conditions for the corrugating medium included a base weight of 120 g/m^{-2}, 10 wt.% bamboo paper sludge solid waste, 0.3 wt.% APAM (Estimated molecular mass of 600 × 10^4 Daltons), and 1.5 wt.% cationic starch. The apparent density, breaking length, and ring crush index were 0.53 g/cm^{-3}, 2.51 km, and 7.48 N/mg^{-1}, respectively, under the best process conditions. This finding could help satisfy the demand for materials used for making the corrugating medium and could support the full utilization of the solid waste of bamboo paper sludge to achieve higher value.

Keywords: Solid waste; Bamboo paper sludge; Corrugating medium; OCC

Contact information: a: International Centre for Bamboo and Rattan, 100102 Beijing, China;
b: School of Forestry and Landscape Architecture, Anhui Agricultural University, 230036, Hefei, China;
** Corresponding authors: nj230036@163.com; feibenhua@icbr.ac.cn*

INTRODUCTION

Papermaking is one of the four great inventions of ancient China that has made outstanding contributions to human civilization. Currently, China leads in both the production and consumption of paper and paperboard. According to the China Paper Association's survey data, the production weight of paper and paperboard was 107.1 million tons in 2015, illustrating the large demand for paper and paperboard (Zhao 2012). Forest resources are diminishing daily, and the wastewater from pulping with grasses is not easily disposable. The wastewater is not of good quality, as it has few fibers in it and restricts the use of natural fibers. The demand for paper must be balanced with forest resource protection. Fortunately, paper factories have begun to use old corrugated container (OCC) pulp to make paper that has an economically beneficial effect. OCC pulp is a good raw material to make paper (Gulsoy and Erenturk 2016; Luo *et al.* 2016; Wang *et al.* 2016). To make up for the shortage of raw wood materials, OCC pulp is used instead of protoplasmic wood (Hu 2005; Xu 2007).

Bamboo, having more than 70 genera and 1200 species, covers an area of 32 million hectares in the whole world. The bamboo mainly is distributed in Asia, Africa, tropical and subtropical area of South America, and is less prominently distributed in temperate and cold zones. Moreover, bamboo forest area is increasing at an annual rate of 3%, providing more bamboo in building products and the papermaking industry, even though the global forest area has been falling sharply. The solid waste of bamboo paper sludge is a byproduct of the pulping and papermaking wastewater treatment that is the final solid waste recovered from the wastewater treatment process in a pulp and paper mill. Currently, the comprehensive utilization of bamboo pulp sludge has the following values: burning, fertilizer application, soil improvement, and other related uses (Wang *et al.* 2009; Cong *et al.* 2011; Zhang and Pan 2011). Most sludge is landfilled or incinerated (Beauchamp *et al.* 2002). However, the costs of landfills are increasing, and the potential of a landfill site contamination must be considered. Incineration is also costly and could potentially cause air pollution problems. Whether placed in a landfill or stacked, bamboo paper sludge solid waste takes up a lot of land and causes environmental pollution. Although some paper mill sludge has the potential to be reused as a soil amendment, the mixture must be in accordance with specific regulations to avoid potential environmental risks that can arise after land restoration (Bonoli *et al.* 2015). Environmental protection is increasingly a priority for the forest products industry (AFPA 2006). Also, the operating cost associated with the sludge handling was often reported to be a significant part of the overall operating cost in the wastewater treatment plant (Teh *et al.* 2016). The development and utilization of bamboo pulp sludge could solve the problem of secondary pollution of the environment, and it also generates certain economic effects (Wang *et al.* 2014). Therefore, the use of this solid waste is an urgent problem that needs to be solved. Previous research has examined wood-based panels, medium-density fiberboard (MDF), and biodegradable paper sheeting (Pang 2008; Wang 2011; Zhang and Pan 2011; Wang *et al.* 2014). These products were all made from bamboo paper sludge. Utilizing bamboo paper sludge increases its value. However, there is almost no literature that deals with the effects of the addition of solid waste to OCC paper to make a corrugating medium. Combining OCC paper and solid waste could decrease the costs of resources and provide added value to waste material.

In this study, bamboo paper sludge solid waste and OCC pulp were used to make a corrugating medium, with anionic polyacrylamide as a retention agent and cationic starch as a strengthening agent. Using a single-factor experiment, the paper properties were compared to find their optimal conditions. These conditions could lead to the full use of waste resources. The results also suggested that the solid material of bamboo paper sludge is an advantageous raw material that can be utilized in papermaking.

EXPERIMENTAL

Materials

The solid waste of bamboo paper sludge (solid waste) was provided by the Guizhou bamboo paper industry in Guizhou province, China. It was the secondary sludge that was derived after wastewater treatment. The characteristics of the bamboo paper sludge are given in Table 1 (Wang *et al*. 2013). The OCC pulp was provided by Shanying Paper Company, Ltd. (Maanshan, Anhui province, China). Its moisture content was about 15%. Anionic polyacrylamide (APAM) was provided by Fengmin Environmental Protection Technology Development Company, Ltd. (Wuxi, Jiangsu province, China), and the cationic starch was provided by Jinye Industrial Company, Ltd. (Renqiu, Hebei province, China). Figure 1 shows the materials used to make the paper.

Table 1. Characteristics of the Used Bamboo Paper Sludge

Ash (%)	Cellulose (%)	Lignin (%)	Extractives (%)
34.96	21.46	3.73	1.78

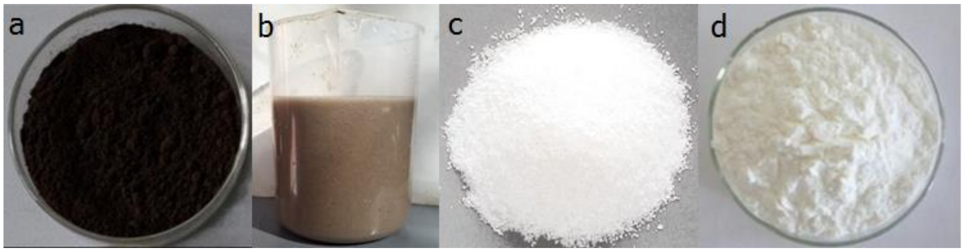

Fig. 1. The materials used to make paper: (a) bamboo paper sludge, (b) OCC pulp, (c) APAM, and (d) cationic starch

Methods

The corrugating medium was made with a density of 120 g/m^{-2}. The estimated molecular mass of APAM, the addition level of APAM, the addition level of cationic starch, and the addition level of solid waste were explored using a single-factor design experimental method. Table 2 shows the four factors and their parameters. Without the additions of APAM and cationic starch, the bamboo paper sludge was not retained successfully in the paper in a preliminary experiment. With the retention and strengthening agents, the addition level of APAM was less than 0.4 wt.%, and the addition level of cationic starch was 1.0%. Therefore, APAM was added at 0.2 wt.%, and cationic starch was added at 1.0% when the other factors were explored. Considering the influence of the solid waste and the data from preliminary experiments, the addition level of the solid waste of bamboo paper sludge was set at 10 wt.%.

Table 2. Single-factor Experimental Design

No.	Estimated Molecular Mass of APAM (Daltons)	Addition of APAM (wt.‰)	Addition of Cationic Starch (wt.‰)	Addition of Bamboo Paper Sludge Solid Waste (wt.%)
1	80 × 104	0.1	0.5	0
2	400 × 104	0.2	1.0	5
3	600 × 104	0.3	1.5	10
4	800 × 104	0.4	2.0	15
5	1000 × 104	-	-	20

Pretreatment

The solid waste had a moisture content of 40% to 50% and was oven-dried at 103 °C ± 2 °C until its final moisture content ranged from 8% to 10%. The dried material was filtered through a 200-mesh (0.075-mm) screen in a sieve. The OCC pulp had a moisture content of 45% to 55% and was processed in a beater for 15,000 revolutions until the beating degree was 45 °SR. Water was added until the OCC pulp consistency was 2%.

Manufacturing

The grammage of the paper was set at 120 g/m^{-2}. First, the solid waste was added to the APAM in a beaker to make a uniform liquid suspension, which was stirred for 2 h at 200 rpm. The cationic starch was added to the OCC pulp to make a mixture. Lastly, the uniform liquid suspension and the starch-pulp mixture were combined to make the paper *via* a paper machine (ZQJ1-B-I, Shanxi Science and Technology Factory, Xianyang, China). After the paper was partially dried using cloth and absorbent paper, the paper was removed from the copper wire mesh and pressed at 0.3 MPa for 10 min in the mill (ZQYCII, Shanxi Science and Technology Factory, Xianyang, China). Each paper was placed between a piece of cloth and a stainless steel plate to keep it smooth, and dry absorbent paper was placed between the paper and cloth to absorb excess water during squeezing. Finally, the paper was dried in the paper machine, and the end products were obtained (Fig. 2).

Fig. 2. End products

Property testing

The grammage, thickness, apparent density, breaking length, compressive strength (ring crush method), and moisture content of the paper were determined in accordance with the standards GB/T 451.2 (2002), GB/T 451.3 (2002), GB/T 12914 (2008), GB/T 2679.8 (1995), and GB/T 462 (2008), respectively. The properties were compared, and the optimum conditions were confirmed according to GB/T 13023 (2008). White water retrieved from the white water recycle system was used to test the retention ratio of the solid waste *via* filtering. The retention ratio of the solid waste was calculated according to Eq. 1,

$$\mathrm{S}R = \frac{W_0 - W_1}{W_0} \times 100\% \qquad (1)$$

where W_o refers to the oven dry quantity of the bamboo paper sludge and OCC, and W_1 refers to the oven dry quantity of white water.

RESULTS AND DISCUSSION

Estimated Molecular Mass of APAM

The factors used to determine the optimal estimated molecular mass of APAM are shown in Table 3. The results are shown in Table 4. The ring crush index is the most important property for the corrugating medium, so it was the primary result evaluated. Number 1 was the corrugating medium with only solid waste; thus it resulted in having the worst properties. Accordingly, the addition of APAM and cationic starch was advantageous to the corrugating medium. When the APAM was added to the OCC pulp, the fibers with a similar charge caused the APAM molecular chain to remain stretched (extended conformation). The larger APAM molecular mass (longer molecular chain) interacted more with the fibers, within a certain range (Zhang *et al*. 2003). The ring crush index increased at first, but then decreased as the estimated molecular mass of the APAM increased. This was because it had positive contact with the fibers, which improved the properties of the papers after the APAM was added to the pulp. However, if the molecular chains of APAM were too long, the APAM had an increased tendency to impart bridging flocculation. Thus, if the estimated molecular mass of APAM was too large, flocculation increased, which reduced the evenness and properties of the paper (Zhang *et al*. 2003). When the estimated molecular mass of the APAM was 600×10^4 (No. 4), the ring crush index was at its highest value, although the apparent density and breaking length of No. 4 were not optimal. However, when No. 4 was compared with the samples with higher apparent density and breaking length, the differences in these properties were not large. Also, the retention ratio of the solid waste was highest in No. 4. Overall, No. 4 (Estimated molecular mass of 600×10^4 Daltons) had the optimum conditions.

Table 3. Experimental Design for Determining Optimal Level of Estimated Molecular Mass of APAM

No.	Estimated Molecular Mass of APAM (Daltons)	Addition of APAM (wt.‰)	Addition of Cationic Starch (wt.‰)	Addition of Bamboo Paper Sludge Solid Waste (wt.%)
1	0	0.2	1	10
2	80×10^4			
3	400×10^4			
4	600×10^4			
5	800×10^4			
6	1000×10^4			

Table 4. Properties of Paper with Various APAM Estimated Molecular Masses

No.	Grammage (g/m^{-2})	Apparent Density (g/cm^{-3})	Breaking Length (km)	Ring Crush Index (N/mg^{-1})	Retention Ratio (%)
1	100.89	0.49	2.28	7.17	50.51
2	114.60	0.50	2.52	7.73	65.53
3	114.08	0.53	2.53	8.02	68.95
4	117.76	0.55	2.52	8.84	73.95
5	114.23	0.47	2.56	8.30	66.05
6	117.42	0.56	2.54	7.82	72.58

Addition Level of APAM

The experimental design regarding the addition level of APAM, with consideration of the optimal estimated molecular mass (600×10^4 Daltons), is shown in Table 5. Table 6 shows the properties of the paper samples under the various addition levels. The apparent density and breaking length first increased and then decreased as the addition of APAM was increased. At the highest dosages the packing materials and fibers were completely surrounded by the APAM (Li and Huang 1996). Also, APAM is an efficient flocculant, even at the low concentration of 0.1 wt.%. However, if the level of APAM is too high, it will make paper material and padding flocculated and non-uniform, giving rise to undesirable properties (Xu 1982). Therefore, the apparent density and breaking length of the paper decreased with higher addition levels, as can be seen in No. 4. Table 6 shows that ring crush index of No. 4 was the largest out of the four samples. However, No. 3 and No. 4 only have a small difference between their ring crush indices. Also, the apparent density and breaking length of No. 3 was the largest. With consideration of using fewer materials, the best addition level of APAM was determined to be 0.3 wt.% (No. 3).

Table 5. Experimental Design for Determining Optimal Addition Level of APAM

No.	Estimated Molecular Mass of APAM (Daltons)	Addition of APAM (wt.‰)	Addition of Cationic Starch (wt.‰)	Addition of Bamboo Paper Sludge Solid Waste (wt.%)
1	600×10^4	0.1	1	10
2		0.2		
3		0.3		
4		0.4		

Table 6. Properties of Paper with Various APAM Addition Levels

No.	Grammage (g/m^{-2})	Apparent Density (g/cm^{-3})	Breaking Length (km)	Ring Crush Index (N/mg^{-1})	Retention Ratio (%)
1	114.89	0.53	2.52	7.67	56.63
2	114.06	0.53	2.46	8.11	57.89
3	114.16	0.60	2.65	8.74	55.26
4	112.62	0.52	2.40	8.78	50.53

Addition Level of Cationic Starch

With respect to the conclusions drawn above, various addition levels of cationic starch were tested, and the experimental design is shown in Table 7. Table 8 shows the properties of paper under the various addition levels. All paper properties increased first, and then some decreased. Most properties were highest when the addition of cationic starch was 1.5 wt.%. Cationic starch can be easily adsorbed onto the surface of fibers, but it also has strong forces at low contents. The cationic starch had strong adsorption to electronegative fibers, packing materials, *etc*. Given the paste liquid quality of cationic starch in cold water and its swelling capacity, starch could help to fill the holes in the paper, which can increase paper properties. If the pulp had too much cationic starch, its charge would be reversed and prevent more cationic starch from adsorbing on the fiber surface (Bai and Han 2009). The best level of cationic starch was 1.5% (No. 3).

Table 7. Experimental Design for Determining Optimal Addition Level of Cationic Starch

No.	Estimated Molecular Mass of APAM (Daltons)	Addition of APAM (wt.‰)	Addition of Cationic Starch (wt.‰)	Addition Level of Bamboo Paper Sludge Solid Waste (wt.%)
1	600×10^4	0.3	0.5	10
2			1	
3			1.5	
4			2	

Table 8. Properties of Paper with Various Cationic Starch Addition Levels

No.	Grammage (g/m^{-2})	Apparent Density (g/cm^{-3})	Breaking Length (km)	Ring Crush Index (N/mg^{-1})	Retention Ratio (%)
1	113.16	0.52	2.18	6.35	63.42
2	107.58	0.54	2.24	6.35	58.16
3	105.97	0.56	2.42	6.96	57.89
4	106.64	0.52	2.39	6.93	59.47

Addition Level of Solid Waste of Bamboo Paper Sludge

The best process conditions for the corrugating medium were an APAM estimated molecular mass of 600×10^4 Daltons, 0.3 wt.% APAM, and 1.5 wt.% cationic starch. The experiments were performed on the premise that the corrugating medium properties were in accordance with standard GB/T 13023 (2008), and making full use of the solid waste to confirm the best addition levels. The experimental design is shown in Table 9, while Table 10 shows the properties of paper under the various addition levels. The apparent density did not have an obvious change, which demonstrated that the addition of solid waste did not have an impact on the apparent density. The breaking length and ring crush index gradually dropped as the solid waste addition level increased. This result indicated that the addition of the solid waste reduced the paper properties. The results suggest that there were more interfaces between OCC pulp and bamboo paper sludge. Moreover, the length and strength of the two fiber were lower after anaerobic digestion than OCC pulp. However, with 10 wt.% bamboo paper sludge solid waste, the apparent density, breaking length, and ring crush index were 0.53 g/cm^{-3}, 2.51 km, and 7.48 N/mg^{-1}, respectively, which met standard GB/T 13023 (2008). Therefore, 10 wt.% bamboo paper sludge solid waste was the best addition level.

Table 9. Experimental Design for Determining Optimal Addition Level of Solid Waste of Bamboo Paper Sludge

No.	Estimated Molecular Mass of APAM (Daltons)	Addition of APAM (wt.‰)	Addition of Cationic Starch (wt.‰)	Addition of Bamboo Paper Sludge Solid Waste (wt.%)
1	600×10^4	0.3	1.5	0
2				5
3				10
4				15
5				20

Table 10. Properties of Paper with Various Addition Levels of Solid Waste of Bamboo Paper Sludge

No.	Grammage (g/m^{-2})	Apparent Density (g/cm^{-3})	Breaking Length (km)	Ring Crush Index (N/mg^{-1})	Retention Ratio (%)
1	108.75	0.52	2.63	8.52	66.84
2	104.58	0.52	2.54	7.43	69.47
3	107.65	0.53	2.51	7.48	69.65
4	107.79	0.52	2.12	6.70	79.47
5	105.23	0.52	1.83	5.78	77.26

CONCLUSIONS

1. This study determined that the solid waste of bamboo paper sludge could be used for papermaking.
2. The best process conditions for the corrugating medium included a basis weight of 120 g/m^{-2}, 10 wt.% bamboo paper sludge solid waste, 0.3 wt.% APAM (Estimated molecular mass of 600×10^4 Daltons), and 1.5 wt.% cationic starch.
3. The apparent density, breaking length, and ring crush index were 0.53 g/cm^{-3}, 2.51 km, and 7.48 N/mg^{-1}, respectively, under the best process conditions, satisfying the standard GB/T 13023 (2008). This process could make full use of the solid waste of bamboo paper sludge and benefit the paper industry by achieving higher added-value.

ACKNOWLEDGMENTS

The authors acknowledge the financial support from The Twelfth Five-Year-Plan in National Science and Technology for the Rural Development in China (Grant No. 2012BAD23B0204). The authors are also thankful for the Institute of Chemical Industry of Forest Products, CAF, for technical guidance, Guizhou bamboo paper industry for supplying materials and for assistance with sampling, and for the help of Hai-Feng Zhu, Fei Zhou, Na-Na Zhang, Fei-Fei Zhang, and Miao Liu in the School of Forestry and Landscape Architecture at Anhui Agricultural University in Anhui province, China.

REFERENCES CITED

American Forest and Paper Association (AFPA) (2006). "Assessing industry technology challenges," *Agenda 2020 Technology Alliance*, (http://www.agenda2020.org), Accessed 16 October 2009.

Bai, C. N., and Han, Q. (2009). "Application of cationic starch and amphoteric starch in papermaking," *Paper Science & Technology* 28(1), 38-41. DOI: 10.3969/j.issn.1671-4571.2009.01.010

Beauchamp, C. J., Charest, M. -H., and Gosselin, A. (2002). "Examination of environmental quality of raw and composting de-inking paper sludge," *Chemosphere* 46(6), 887-895. DOI: 10.1016/S0045-6535(01)00134-5

Bonoli, A., Bortolotti, V., Dall'Ara, A., Macini, P., and Vannini, M. (2015). "Magnetic resonance analysis of carbon content in paper mill sludge–soil mixtures used in remediation practices," *International Journal of Environmental Science and Technology* 12(1), 237-246.

Cong, G. P., Shi, Y. Q., Ding, L. B., Pan, A. X., Shi, F., and Fang, G. G. (2011). "Biomass resource utilization of paper mill sludge," *Biomass Chemical Engineering* 45(5), 37-45. DOI: 10.3969/j.issn.1673-5854.2011.05.008

China Paper Association (2012). "The 2012 annual report on China's papermaking industry," *China Paper* 34(11), 10-21.

GB/T 451.2 (2002). "Paper and board- Determination of size and deviation," Standardization Administration of China, Beijing, China.

GB/T 451.3 (2002). "Paper and board – Determination of grammage," Standardization Administration of China, Beijing, China.

GB/T 12914 (2008). "Paper and board – Determination of tensile properties," Standardization Administration of China, Beijing, China.

GB/T 2679.8 (1995). "Paper and board – Determination of compressive strength – Ring crush method," Standardization Administration of China, Beijing, China.

GB/T 462 (2008). "Paper, board, and pulp – Determination of moisture content of analytical sample," Standardization Administration of China, Beijing, China.

GB/T 13023 (2008). "Corrugating medium," Standardization Administration of China, Beijing, China.

Gulsoy, S. K., and Erenturk, S. (2016). "Improving strength properties of recycled and virgin pulp mixtures with dry strength agents," *Starch-Stärke* 66, 1-8. DOI: 10.1002/star.201600035

Hu, Z. Y. (2005). "A reflection on the situation and tasks of China's paper industry at present," *China Paper* 26(12), 19-22. DOI: 10.3969/j.issn.1007-9211.2005.12.003

Li, Z. B., and Huang, N. H. (1996). "PAM papermaking retention agent and its correct application," *Shanxi Chemical Industry* 2, 41-42.

Luo, Q., Liu, L., Zhang, A. L., Jing, L. M., and Zhang, D. (2016). "Study on characteristics of OCC papermaking sludge," *China Pulp & Paper* 35(5), 22-28.

Teh, C. Y., Budiman, P. M., Shak, K. P. Y., and Wu, T. Y. (2016). "Recent advancement of coagulation-flocculation and its application in wastewater treatment," *Industrial and Engineering Chemistry Research* 55(16), 4363-4389.

Wang, C. G., Jiang, Z. H., Liu, X. M., and Fei, B. H. (2009). "Research advance of utilization of paper sludge," *China Pulp & Paper* 28(1), 64-68. DOI: 10.3969/j.issn.0254-508X.2009.01.015

Wang, C. G., Chen, M. L., Jiang, Z. H., Zhang, S. Y., Wu, H., Wang, X., Pei, Y. W., and Liu, C. Q. (2014). "Biodegradable paper sheeting as agricultural covering with incorporation of bamboo pulp sludge," *BioResources* 9(3), 4128-4137. DOI: 10.15376/biores.9.3.4128-4137

Wang, X., Wang, C. G., Zhang, S. Y., Pei, Y. W., and Chen, M. L. (2013). "Characteristic of bamboo paper sludge by means of Fourier transform infrared and elemental analysis," *Advanced Materials Research* 712-715, 443-447. DOI: 10.4028/www.scientific.net/AMR.712-715.443

Wang, X.-D., Zhao, C.-S., Jiang, Y.-F., and Han, W.-J. (2016). "Research on mechanical combined with biological modification of OCC pulp to improve the strength of paper," in: *International Workshop on Material Science and Environmental Engineering*, Wuhan, Hubei, China, 48-56. DOI: 10.1142/9789813143401_0006

Xu, Z. K. (1982). "Features and application of APAM polymer retention agent," *Shanghai Papermaking* 2, 8-36.

Xu, M. (2007). "The development of waste paper pulp in China and abroad," *Jiangsu Papermaking* 3, 17-21.

Zhang, A. L., and Pan, M. L. (2011). "Basic properties of paper mill sludge and its utilization," *Paper and Paper Making* 30(1), 50-53. DOI: 10.3969/j.issn.1673-5854.2011.05.008

Zhang, H. W., Tang, A. M., Chen, G., Xie, G. H., and Yang, K. Y. (2003). "Effects of CPAM/APAM compound on paper strength," *China Pulp & Paper* 22(11), 18-20. DOI: 10.3969/j.issn.0254-508X.2003.11.005

Zhao, R. (2012). *Study on the Trading and Environment Effect of China's Paper Industry*, Master's Thesis, Yunan University, Kunming, China.

Article submitted: November 17, 2016; Peer review completed: February 6, 2017; Revised version received and accepted: February 13, 2017; Published: March 8, 2017.
DOI: 10.15376/biores.12.2.3133-3142