Effects of Moisture Content and Temperature on the Quality of Water Hyacinth Pellets

Xia Zhang, Zongshou Cai,* Lihong Chen, Dezhen Zhang, and Zhe Zhang

Moisture content and temperature are two important process parameters that greatly influence the quality of biomass pellet fuels. The moisture content of raw material was varied at five levels (8%, 10%, 12%, 14%, 16%) to test its effect on water hyacinth pellet density and diametric compression strength. The experimental conditions included a compressing force of 6 kN, hammer mill screen size of 2 mm, and temperature of 100 °C. Five temperature conditions (80, 90, 100, 110, and 120 °C) were studied under the same conditions and 12% moisture content. In these conditions, the optimal moisture contents for water hyacinth pellet density and diametric compression strength were 12.2% and 11.5%, respectively, and the optimal temperatures were 100.4 °C and 104.3 °C, respectively.

Keywords: Water hyacinth; Biomass; Pellets fuel; Moisture content; Temperature; Pellet density; Diametric compression strength

*Contact information: Department of Mechanical and Electrical Engineering, Yunnan Agricultural University, Kunming 650201, China; *Corresponding author: 1395318154@qq.com*

INTRODUCTION

Water hyacinth (WH) has a strong ability to absorb nitrogen (N), phosphorus (P), and other harmful heavy metal elements from water, and it has become an ecological hero, being widely used in the ecological rehabilitation of water bodies (Wang *et al*. 2012; Chibueze *et al*. 2014; Zhang *et al*. 2014). For example, in the “comprehensive treatment project of water environment” in Taihu River Basin, China, the planting area of WH is about 4700 hectares, and the annual output of WH in Taihu Lake is about 2 million tons. As a result, the problem of resource utilization of WH planted for purification of sewage has become more important. Because WH is high in cellulose content (20%) and hemicellulose content (33%), it can be transformed into biomass fuel (Anjanabha and Pawan 2010; Ahn *et al*. 2012; Yang *et al.* 2014). Using mechanical force, WH can be extruded or compressed into biomass pellets with a high volume density and caloric value and uniform size and shape; as fuel, these pellets are more convenient for storage, transportation, and combustion. WH pellet fuel could be an important way to utilize WH as an energy source.

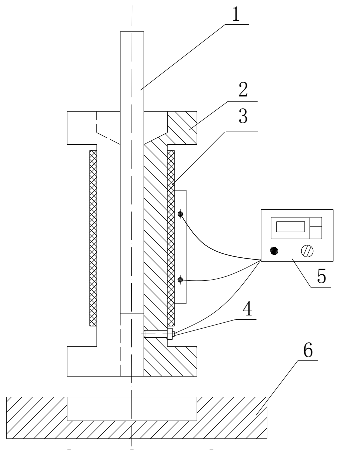
Biomass sources with different chemical compositions require different process parameters for their densification (Kashaninejad and Tabil 2011; Stelte *et al*. 2011; Samuelsson *et al*. 2012; Ståhl *et al*. 2012). Moisture content and temperature are two important process parameters that greatly influence the quality of biomass fuel pellets. For example, with the conditions of 150 MPa pressure, 9.4% moisture content, hammer mill screen size of 2 mm, and increasing the process temperature from 25 °C to 85 °C, the pellet density of corn cob can be increased by 15.4% (Kaliyan and Morey 2010). With a pellet diameter of 5.9 mm and pellet mill rotation rate of 235 rpm, the pellet density of bamboo increased by 24.9% when the moisture content of the raw material was increased from 8% to 16% (Liu *et al.* 2012).

So far, there have been few studies into the use of WH and other aquatic plants as a sources of biomass fuel pellets. This study used regression analysis to investigate the effects of moisture content and temperature on the quality of WH pellets. The optimal moisture contents and temperatures were obtained for WH pellet density and diametric compression strength. Thus, this paper provides a theoretical basis for the industrial production of high-quality WH pellets.

EXPERIMENTAL

Apparatus

The laboratory compaction experiments on WH pellets were carried out on an in-house manufactured pellet apparatus. The apparatus was composed of a plunger, die, heating element, temperature sensor, temperature controller, and base plate (Fig. 1). The cylindrical die was 8 mm in diameter and 160 mm long. A heating element was wrapped on the outer surface of the cylindrical die and was operated by a temperature controller. The temperature of the die was measured by a temperature sensor, which was fixed to the inside of the cylinder wall close to the base plate. The temperature sensor was also connected to the temperature controller. The die was covered by insulating material and installed on a stainless steel base plate. The plunger was attached to the upper moving crosshead of an electronic universal testing machine (Model CMT6104, MTS - SANS Shenzhen Operations, Shenzhen, China) and moved vertically.



1. plunger 2. die 3. heating element 4. temperature sensor 5. temperature controller 6. base plate

Fig. 1. Schematic diagram of test apparatus for biomass pellets

Materials

Water hyacinth was collected in October 2014 from the Dianchi Lake, Mingbo Field, Kunming, China. After being mechanically harvested and pressed, the moisture content of fresh WH dropped from 95% to 60 to 70%. The WH residue was stored outdoors for 1 to 2 weeks until its moisture content dropped to 20%. The sun-dried WH residue was ground with a hammer mill with screen sizes of 2 mm, and the initial moisture content of the ground raw WH material was measured using the method of State

Standard of the People's Republic of China GB/T 14095-2007 (Standards of People's Republic of China, 2007). Briefly, 100 g of ground raw material (wet weigh W_1) was placed in a drying oven at 103 ± 2 °C for 8 h. The dried material was moved from the oven to a desiccator for cooling to room temperature. The mass of the oven-dried raw material (dry weight W_2) was determined, and the initial moisture content of the raw WH material was calculated as 12.4% using Eq. 1,

$$M(\%) = \frac{W_1 - W_2}{W_1} \times 100\% \tag{1}$$

where M is the initial moisture content of the raw material, W_1 is the wet weight of the raw material (g), and W_2 is the dry weight of the raw material (g).

The moisture content of different particle sizes of ground materials were conditioned to 8%, 10%, 12%, 14%, and 16%. For conditioning to 8%, 10%, and 12%, a predetermined amount of water was dehydrated by using a drying oven set to 103 ± 2 °C. For conditioning to 14% and 16%, a predetermined amount of water was sprayed uniformly on the material with an atomizer. The conditioned material was stored in sealed plastic bags at 5 °C for a minimum of 72 h prior to use.

The bulk density of WH raw material was measured by calculating the mass of ground raw material that occupied a 500-mL glass cylindrical container. The container was softly tapped three to five times on a wood table during the filling process. The mass per unit volume of ground raw material was calculated as 220 kg/m^3 using Eq. 2,

$$BD = [m_1 - m_2] / V \tag{2}$$

where BD is the bulk density of ground raw material (kg/m^3), m_1 is the total mass of the ground raw material and the cylindrical container (kg), m_2 is the mass of the cylindrical container (kg), and V is the volume of the cylindrical container (m^3).

Preparation of Pellets

Higher pellet density and diametric compression strength indicate better quality biomass pellets (Adapa *et al.* 2009; Kaliyan and Morey 2010; Liu *et al.* 2012, 2014). In this paper, pellet density and diametric compression strength were also used as the two indexes to evaluate the quality of WH pellets produced with different process parameters. During the densification of most biomass, the optimal moisture content of the raw material is between 8% and 16%, and the optimal process temperature is between 80 and 120 °C (Kashaninejad and Tabil 2011; Stelte *et al*. 2011; Samuelsson *et al.* 2012; Ståhl *et al*. 2012). The center points and the edge points of the two process parameters were included in this study, such that the five variations in moisture content and temperature tested were 8%, 10%, 12%, 14%, and 16% and 80, 90, 100, 110, and 120 °C, respectively. The fixed factors were the compressing force of 6 kN and hammer mill screen size of 2 mm.

In the single factor experiment on the effects of moisture content, a known amount (1.1 g) of WH raw material with five variations in moisture content (8%, 10%, 12%, 14%, and 16%) was placed in the compressing chamber of the die through the charging opening. The temperature of the die was set at 100 ± 2 °C *via* the temperature controller. The die was heated to 100 ± 2°C. A maximum load of 6 kN was used on an electronic universal testing machine, and its crosshead speed was set at 50 mm/min. The WH raw material was compressed by the plunger, and the load of the electronic universal testing machine was increased gradually. When the load reached the maximum of 6 kN, the plunger was stopped and maintained in the same position for 5 s to prevent a springback effect. The final product in the compressing chamber was the compressed WH pellet.

In the single factor experiment on the effects of temperature, the WH raw material was heated in a drying oven. An amount of water predetermined by Eq. 1 was removed from the WH raw material; the moisture content was uniformly adjusted from 12.4% to 12%. A known amount (1.1 g) of WH raw material was placed in the compressing chamber of the die through the charging opening. The temperature of the die was set to 80, 90, 100, 110, or 120 ± 2 °C. The load, crosshead speed, and retaining time of the electronic universal testing machine were described above.

The WH pellets compressed with different process parameters were ejected from the die with the plunger and stored separately in sealed plastic bags for one month. The pellet diameter and length were determined using a digital calipers. Pellet mass was also measured with a digital scale. Therefore, the pellet density was calculated. Additionally, the diametric compression strength of pellet was measured using an electronic universal testing machine (Model CMT6104, MTS - SANS Shenzhen Operations, Shenzhen, China). An individual pellet was placed horizontally on the lower bench of the electronic universal testing machine. A diametric load from the upper bench of the testing machine was pressed on the pellet at a speed of 1 mm/min until the fracture of the pellet was observed. The failure load was recorded as diametric compression strength of the pellet.

Regression Analysis and Modeling

To further investigate the effects of moisture content and temperature on WH pellet density and diametric compression strength and to determine the optimal parameters for high quality WH pellets, regression analysis and modeling were performed with SPSS 17.0 (SPSS Inc., Chicago, USA) statistical analysis software. The pellet density and diametric compression strength were set as the objective functions, and the moisture content and temperature were set as the independent variables. Scatterplot analysis showed that the relationships between the objective functions and the independent variables were nonlinear. Therefore, nonlinear models, including the power model, exponential model, logarithmic model, and the quadratic model, were used in the regression analysis. The quadratic model gave the best determination coefficient (R^2) to the experimental data and was subsequently used for regression analysis, using Eq. 3,

$$f(x) = B_2 x^2 + B_1 x + B_0 \tag{3}$$

where $f(x)$ is the objective function (pellet density or diametric compression strength), x is the independent variable (moisture content or temperature), and B_0, B_1, and B_2 are the undetermined coefficients of regression.

RESULTS AND DISCUSSION

Results

Approximately 150 WH pellets were produced from each variation in processing parameters, and 10 pellets were randomly selected for testing. Their mass, length, and diameter were measured, and their mean pellet density was calculated (Tables 1 and 2).

The mean diametric compression strength of ten test objects from each sample was calculated (Tables 1 and 2).

The ANOVA analyses were performed to understand the effects of the moisture content and temperature on the pellet density and diametric compression strength of WH pellets. The results showed that both the pellet density and diametric compression strength of WH pellets were significantly affected by moisture content and temperature ($P<0.05$).

Table 1. Pellet Density and Diametric Compression Strength at Various Moisture Contents

Moisture Content (%)	Compressing Force (kN)	Temperature (°C)	Mass (g)	Particle Length (mm)	Pellet Density (kg.m^{-3}) *	Diametric Compression Strength (kN) *
8	6	100	1.1	16.61	1318.0	1.20
10			1.1	16.21	1350.3	1.38
12			1.1	16.05	1364.0	1.42
14			1.1	16.22	1350.1	1.27
16			1.1	16.48	1328.8	1.10

* indicates ANOVA analyses at 5% level of significance. Same as the following table.

Table 2. Pellet Density and Diametric Compression Strength at Various Temperatures

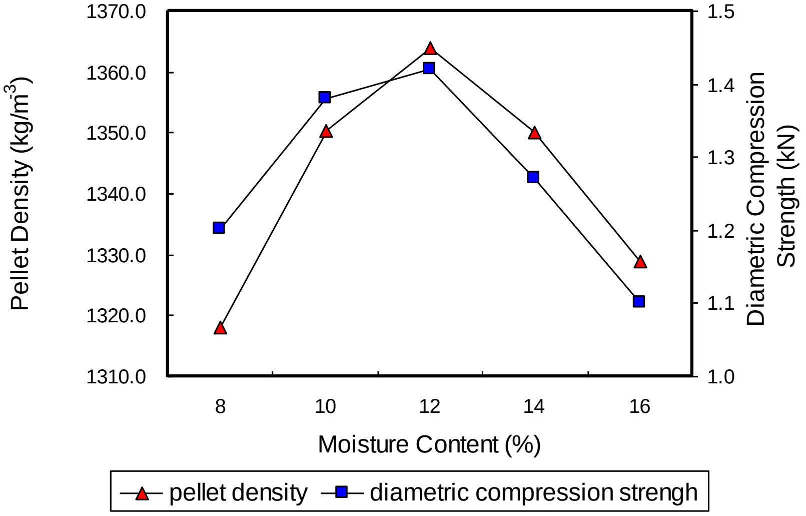
Temperature (°C)	Compressing Force (kN)	Moisture Content (%)	Mass (g)	Particle Length (mm)	Pellet Density (kg.m^{-3}) *	Diametric Compression Strength (kN) *
80	6	12	1.1	17.31	1264.3	0.91
90			1.1	16.34	1340.0	1.18
100			1.1	16.01	1367.9	1.39
110			1.1	16.46	1330.4	1.24
120			1.1	17.14	1277.5	0.88

Analyses

Effect of moisture content

Under the conditions of 6 kN compressing force, 2-mm hammer mill screen, and 100 °C temperature, the effects of moisture content on WH pellet density and diametric compression strength were examined (Fig. 2). With increasing initial moisture content, the pellet density and diametric compression strength initially increased but eventually decreased. When the moisture content increased from 8% to 12%, the pellet density and diametric compression strength increased from 1318 to 1364 kg/m^3 and from 1.2 to 1.42 kN, which represented 3.5% and 18.3% increases, respectively. In contrast, when moisture content further increased to 16%, the pellet density and diametric compression strength decreased to 1328.8 kg/m^3 and 1.1 kN, which were reductions of 2.5% and a 22.5%, respectively.

Proper moisture content was an important process parameter for producing high-quality WH pellets. As water in the raw material acts as a binder of biomass particles by facilitating starch gelatinization, protein denaturation, and partial solubilization of some of the chemical components during the densification process, it strengthens and promotes bonds between biomass particles, thus improving the integrity of biomass pellets. However, excess water that cannot be absorbed by particles attaches to the biomass surface, which impedes particle compaction and reduces pellet quality.

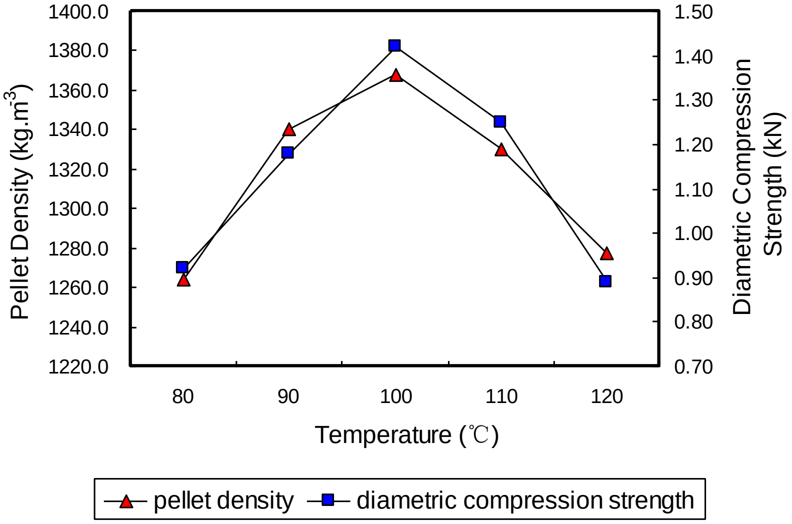


Fixed factors were set as compressing force of 6 kN, hammer mill screen size of 2 mm, and temperature of 100 °C.

Fig. 2. Effect of moisture content on WH pellet density and diametric compression strength

Effect of temperature

Under the conditions of 6 kN compressing force, 2-mm hammer mill screen, and 12% moisture content, the effects of temperature on WH pellet density and diametric compression strength were observed (Fig. 3).



Fixed factors were set as compressing force of 6 kN, hammer mill screen size of 2 mm, and moisture content of 12%.

Fig. 3. Effect of temperature on WH pellet density and diametric compression strength

With increasing temperature, both pellet density and diametric compression strength initially increased but eventually decreased. When temperature was increased from 80 to 100 °C, the pellet density and diametric compression strength increased from 1264.3 to 1367.9 kg/m^3 and from 0.91 to 1.39 kN, which reflected 8.2% and 52.7% increases, respectively. However, when was temperature increased from 100 to 120 °C, the pellet density and diametric compression strength dropped to 1277.5 kg/m^3 and 0.88 kN, which were decreases of 6.6% and 36.7%, respectively.

Thus, temperature noticeably influenced WH pellet density and diametric compression strength. Higher temperature promotes the plastic deformation of biomass particles and enhances permanent bonding between particles. However, WH pellets were slightly discolored and charred at process temperatures above 110 °C, which was unfavorable to the densification process. These imperfections may have lowered WH pellet quality.

Result of regression analysis

Table 3 shows the regression equations between the objective functions and the independent variables and significance tests of the regression at a 0.05 significance level. Regression curves are shown in Fig. 4.

Table 3. Results of Regression Equations and Significance Tests

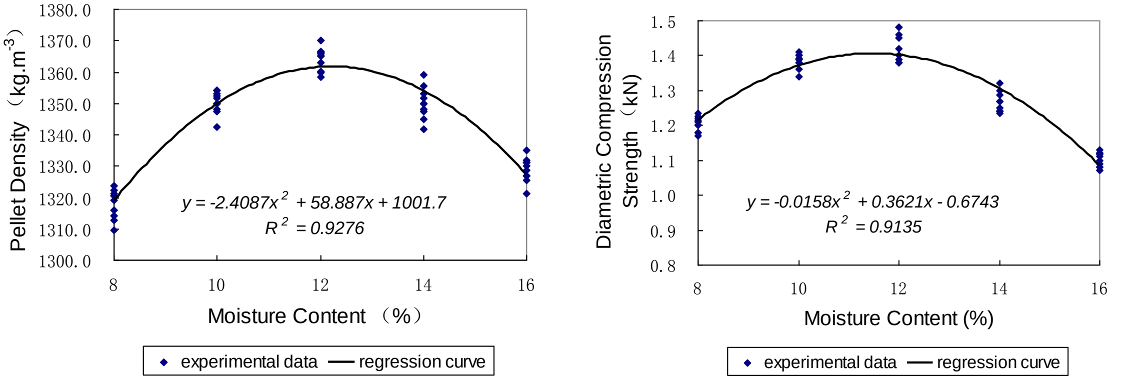
Independent Variable	Objective Function	Regression Equation	R^2	F	Sig.
Moisture Content (%)	Pellet Density (kg.m^{-3})	$y=-2.4087x^2+58.887x+1001.7$	0.9276	300.913	0.000**
	Diametric Compression Strength (kN)	$y=-0.0158x^2+0.3621x-0.6743$	0.9135	248.275	0.000**
Temperature (°C)	Pellet Density (kg.m^{-3})	$y=-0.2305x^2+46.264x-959.49$	0.9397	366.097	0.000**
	Diametric Compression Strength (kN)	$y=-0.0011x^2+0.2295x-10.123$	0.9377	353.642	0.000**

** indicates that the regression relationship of equation was very significant ($p < 0.01$) for n = 49.

As shown in Table 3, the coefficients of determination for the regression equations between moisture content and pellet density or diametric compression strength were 0.9276 or 0.9135, respectively, which meant that they accounted for 92.76% or 91.35% of the variance.

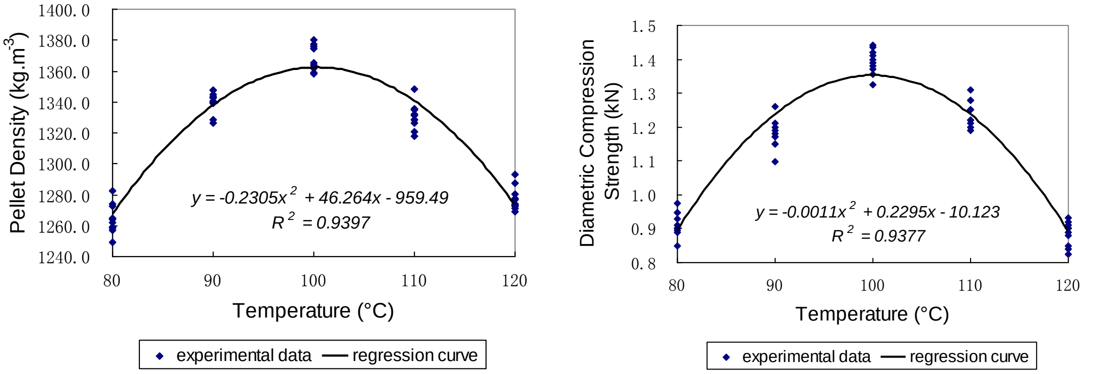
The coefficients of determination of the regression equations between temperature and pellet density or diametric compression strength were 0.9397 or 0.9377, respectively, which meant that 93.97% or 93.77% of the variance was explained. Significance tests of the regression equations demonstrated that $p < 0.01$ for all four equations, indicating that the predicted results were in accordance with the experimental data.

By calculating the extreme values of the four regression equations, the optimal moisture contents for highest pellet density and diametric compression strength were obtained as 12.2% and 11.5%, respectively, while the optimal temperatures were 100.4 °C and 104.3 °C, respectively.



a. b.

Fixed factors were set as compressing force of 6 kN, hammer mill screen size of 2 mm, and temperature of 100 °C



c. d.

Fixed factors were set as compressing force of 6 kN, hammer mill screen size of 2 mm, and moisture content of 12%

Fig. 4. Scatter-plots and regression curves between objective functions and dependent variables

CONCLUSIONS

1. With conditions of a compressing force of 6 kN, hammer mill screen size of 2 mm, and temperature of 100 °C, increasing moisture content in raw material was initially associated with increased WH pellet density and diametric compression strength. Higher moister content caused these values to decrease.
2. The regression equations between moisture content and WH pellet density and diametric compression strength were quadratic functions, and their relationships were extremely significant.
3. Under the condition of 100 °C temperature, the optimal moisture contents for pellet density and diametric compression strength were 12.2% and 11.5% respectively.
4. With fixed conditions set at a compressing force of 6 kN, hammer mill screen size of 2 mm, and moisture content of 12%, increasing process temperature was initially associated with increasing WH pellet density and diametric compression strength. Higher temperatures caused these values to decrease.
5. The regression equations between temperature and WH pellet density and diametric compression strength were also quadratic functions, and their relationships were extremely significant too.

6. When moisture content of WH material was 12%, the optimal temperatures for pellet density and diametric compression strength were 100.4 °C and 104.3 °C respectively.

ACKNOWLEDGMENTS

The authors are grateful for the support of the National Natural Science Foundation of China (No. 51265051).

REFERENCES CITED

Adapa, P. K., Tabil, L. G., and Schoenau, G. J. (2009). “Compression characteristics of selected ground agricultural biomass,” *Agricultural Engineering International: The CIGR Ejournal* 11(6), 1-19.

Ahn, D. J., Kim, S. K., and Yun, H. S. (2012). “Optimization of pretreatment and saccharification for the production of bioethanol from water hyacinth by Saccharomyces cerevisiae,” *Bioprocess and Biosystems Engineering* 35(1), 35-41. DOI: 10.1007/s00449-011-0600-5

Anjanabha, B., and Pawan, K. (2010). “Water hyacinth as a potential biofuel crop,” *Electronic Journal of Environmental, Agricultural and Food Chemistry* 9(1), 112-122.

Chibueze, G. A., Mynepalli, K. C. S., and Akinwale, O. C. (2014). “Performance evaluation of a water hyacinth based institutional wastewater treatment plant to mitigate aquatic macrophyte growths at Ibadan, Nigeria,” *International Journal of Applied Science and Technology* 4(3), 117-124.

Kaliyan, N., and Morey, R. V. (2010). “Densification characteristics of corn cobs,” *Fuel Processing Technology* 91(5), 559-565. DOI: 10.1016/j.fuproc.2010.01.001

Kashaninejad, M, and Tabil, L. G. (2011). “Effect of microwave-chemical pre-treatment on compression characteristics of biomass grinds,” *Biosystems Engineering* 108(1), 36-45. DOI: 10.1016/j.biosystemseng.2010.10.008

Liu, Z. J., Jiang, Z. H., Cai, Z. Y., Fei, B. H., Yu Y. and Liu X. (2012). “The manufacturing process of bamboo pellets,” *Proceedings of the 55th International Convention of Society of Wood Science and Technology*, Beijing, China.

Liu, Z. G., Quek, A., and Balasubramanian, R. (2014). “Preparation and characterization of fuel pellets from woody biomass, agro-residues and their corresponding hydrochars,” *Applied Energy* 113, 1315-1322. DOI: 10.1016/j.apenergy.2013.08.087

Samuelsson, R., Larsson, S. H., Thyrel, M., and Lestander, T. A. (2012). “Moisture content and storage time influence the binding mechanisms in biofuel wood pellets,” *Applied Energy* 99, 109-115. DOI: 10.1016/j.apenergy.2012.05.004

Ståhl, M., Berghel, J., Frodeson, S., Granstrom, K., and Renstrom, R. (2012). “Effects on pellet properties and energy use when starch is added in the wood-fuel pelletizing process,” *Energy and Fuels* 26(3), 1937-1945. DOI: 10.1021/ef201968r

Standards of People's Republic of China. 2007. GB/T 14095: Drying technology of agricultural products-Terminology. Standardization Administration of the People's Republic of China, SAC.

Stelte, W., Holm, J. K., Sanadi, A. R., Barsberg, S., Ahrenfeldt, J., and Henriksen, U. B. (2011). “Fuel pellets from biomass: The importance of the pelletizing pressure and its dependency on the processing conditions," *Fuel* 90(11), 3285-3290. DOI: 10.1016/j.fuel.2011.05.011

Wang, Z., Zhang, Z., Zhang, J., Zhang, Y., Liu, H., and Yan, S. (2012). "Large-scale utilization of water hyacinth for nutrient removal in Lake Dianchi in China: The effects on the water quality, macrozoobenthos and zooplankton," *Chemosphere* 89(10), 1255-1261. DOI: 10.1016/j.chemosphere.2012.08.001

Yang, X. R., Liang, J. H., Xu, W. L., Miao, Q. S., and Zhu, J. L. (2014). "Biogas production by the fermentation of water hyacinth enhanced by solid bases," *Journal of Beijing University of Chemical Technology (Natural Science Edition)* 41(1), 83-89. DOI: 10.13543/j.cnki.bhxbzr.2014.01.018

Zhang, Z., Gao, Y., and Guo, J. (2014). "Practice and reflections of remediation of eutrophicated water: A case study of haptophyte remediation of the ecology of Dianchi," *Journal of Ecology and Rural Environment* 4(3), 117-124.

Article submitted: September 26, 2015; Peer review completed: November 23, 2015; Revised version received and accepted: November 26, 2015; Published: December 16, 2015.
DOI: 10.15376/biores.11.1.1407-1416