Original Article
Journal of Biosystems Engineering

J. of Biosystems Eng. 40(3):296-304. (2015. 9)
http://dx.doi.org/10.5307/JBE.2015.40.3.296

eISSN : 2234-1862
pISSN : 1738-1266

Estimation of Moisture Content in Comminuted Miscanthus based on the Intensity of Reflected Light

Yongjin Cho[1], Dong Hoon Lee[2]*

[1]*Dept. of Bio-Mechatronic Engineering, Sungkyunkwan University, Suwon, Korea*
[2]*Dept. of Bio-systems Engineering, Chungbuk National University, Cheongju, Korea*

Received: August 10th, 2015; Revised: August 25th, 2015; Accepted: August 31st, 2015

Abstract

Purpose: The balance between miscanthus production and its cost effectiveness depends greatly on its moisture content during post processing. The objective of this research was to measure the moisture content using a non-destructive and non-contact methodology for in situ applications. **Methods:** The moisture content of comminuted miscanthus was controlled using a closed chamber, a humidifier, a precision weigher, and a real-time monitoring software developed in this research. A CMOS sensor equipped with 50× magnifier lens was used to capture magnified images of the conditioned materials with moisture content level from 5 to 30%. The hypothesis is that when light is incident on the comminuted particles in an inclined manner, higher moisture content results in light being reflected with a higher intensity. **Results:** A linear regression analysis for an initiative hypothesis based on general histogram analysis yielded insufficient correlations with low significance level (<0.31) for the determination coefficient. A significant relationship (94% confidence level) was determined at level 108 in a reverse accumulative histogram proposed based on a revised hypothesis. A linear regression model with the value at level 108 in the reverse accumulative histogram for a magnified image as the independent variable and the moisture content of comminuted miscanthus as the dependent variable was proposed as the estimation model. The calibrated linear regression model with a slope of 92.054 and an offset of 32.752 yielded 0.94 for the determination coefficient (RMSE = 0.2%). The validation test showed a significant relationship at the 74% confidence level with RMSE 6.4% (n = 36). **Conclusions:** To compensate the inconsistent significance between calibration and validation, an estimation model robust against various systematic interferences is necessary. The economic efficiency of miscanthus, which is a promising energy resource, can be improved by the real-time measurement of its crucial material properties.

Keywords: Comminution, Histogram, Miscanthus, Moisture content, Real-time measurement

Introduction

There has been increased interest in using biomass in recent times as this would help conserve conventional energy resources. Among various biomass resources, Miscanthus (*Miscanthus × giganteus*) is gaining importance as a very valuable resource owing to its non-food utilization against the background of the worsening global food crisis. In the biomass production and application industry, certain material properties, namely, comminuted size (Miao et al., 2011), compressed density (Sokhansanj et al., 2006; Hess et al., 2009), and moisture content (Consentiono et al., 2007), are the major factors that affect economical and energy efficiency. Generally, in South Korea, the harvesting season of miscanthus for a one-year round crop is when its moisture content is sufficiently low to prevent excess costs in various pathways for post processing (i.e., for transportation, drying, and maintaining thermal potential efficiency). Further, one of the most important trade-offs between production and cost effectiveness of miscanthus is that the balance depends greatly on the moisture content during post processing (Danalatos et al., 2006). Miscanthus is commonly used in the form of pellets for domestic

***Corresponding author:** Dong Hoon Lee
Tel: +82-43-261-2582; **Fax:** +82-43-271-4413
E-mail: leedh@cbnu.ac.kr

heating or generating electric power. Pelletizing miscanthus involves various processes such as transportation, storage, and compression, and the moisture content of the raw material plays a crucial role in determining the economic profit or loss during these processes (Holt et al., 2006; Arabhosseini et al., 2010). The post processing methodology, logistic plans, storage facilities, and consumer practices are decided based on the quantification of the moisture content in pelletized miscanthus.

The pelletizing process mainly consists of two procedures-comminution and compression, which is owing to the initial low density (<150 g/L; Holt et al., 2006) of the raw material. Generally, these two processes are performed through one pathway of a batch process. In the process of comminution, raw materials are transformed into comminuted particles of the minimum possible size (1~10 mm; Miao et al., 2011) by means of a hammer mill or knife mill. The compression process has a relatively higher power consumption than previous process because the output should have high density. Although the moisture content should be high for satisfying the constraints of high density and surface tension in order to realize the shape of a pellet, reducing the thermal potential energy accumulated by water is a challenge. The comminuted particles should have an appropriate moisture content (<15%; Miao et al., 2011) in order to ensure the quality of the pelletized output in terms of density and thermal efficiency. Therefore, accurate quantification of the moisture content in comminuted particles is necessary for guaranteeing the cost and energy efficiency of biomass production using miscanthus.

ASAE S352.2 standard is commonly applied to measure the moisture content of particles such as grains or seeds. According to the standard, one of the most common methods to measure the moisture content of particles of agricultural products is the classic laboratory method called loss on drying (LOD) by heating in an oven for 24 h. The LOD presents a promising methodology to quantify the moisture content of miscanthus in various forms such as harvested crops, fraction of bales, and resulting products (e.g., pellet and communicated resources for boilers). Nevertheless, real-time quantification cannot be carried out during the process between post comminution and pre compression owing to the limitation of the LOD method. The wide range of moisture content (1~35%; Arabhosseini et al., 2010) prior to the comminution process is influenced by the ambient relative humidity and temperature; hence, it is important to maintain an appropriate moisture content corresponding to the requirements of the resulting product, and this is a very challenging task. Further, the most suitable drying and storage method is chosen depending on the moisture content of the comminuted miscanthus, and thus, the method depends greatly on the accurate quantification of moisture content during real-time processing.

The ranges and limitations of measurement systems corresponding to previous representative non-destructive moisture measurement methods are summarized in Table 1.

Among the various non-destructive methods for measuring moisture content, some methods (e.g., NMR, microwave attenuation, and frequency domain) have a systematic disadvantage when studying compound materials such as the comminuted miscanthus. In addition, from the perspective of in situ applications designed for examining materials rapidly both on a constantly moving conveyer belt installed between the comminution and compression machinery and inside a storage chamber for moisture content conditioning, methods such as infrared reflectance, neutron moderation, and microwave attenuation require the static construction of a measurement system but have insufficient capability of deployment. In particular, a specific and locally optimized estimation model for measuring the moisture content of comminuted miscanthus by a non-destructive approach has not been sufficiently studied.

Therefore, the objective of this research was to measure

Table 1. Limitations of non-destructive methods for measuring moisture content

Methods	Range (%)	Limitation
Infrared reflectance (Martin, 1993)	0.02–100	Need for small optical path
NMR (Carr-Brion, 1986)	0.05–100	Need to avoid magnetic materials
Neutron moderation (Kodama et al., 1985)	0.5–100	Less popular
Microwave attenuation (Wignerom et al., 1995)	0–85	Need to avoid metallic materials
Time domain reflectometry (Dalton et al., 1986)	0–100	Complex data analysis
Frequency domain (Hilhorst et al., 1994)	0–100	Single frequency for non-compounds

the moisture content of comminuted miscanthus by a non-destructive non-contact methodology. A CMOS sensor equipped with a 50× magnifier lens was used to capture a magnified image of comminuted miscanthus with the moisture content ranging from 5 to 30%. Theoretically, a histogram analysis was performed using the captured images of the raw material; this analysis was based on the hypothesis that when light is incident on the comminuted particles in an inclined manner, a higher moisture content results in light being reflected with a higher intensity. In order to avoid the effect of inconsistent brightness of the incident light caused by the instability of the source and ambient light, an experimental factor of brightness was limited around 600 lux.

(a) (b) (c)

Figure 1. (a) Baled miscanthus, (b) the process of chipping, and (c) chipped miscanthus.

(a) (b) (c)

Figure 2. (a) Chipped and air-dried miscanthus, (b) the hammer mill, and (c) comminuted miscanthus.

Materials and Methods

Raw material preparation

In this study, one-year-old miscanthus crops were used as raw materials. These were grown at a biomass production field in YungPo area, Iksan city, in 2012, and had been harvested in late March 2013. The initial moisture content of the harvested crops varied from 15 to 30%. The harvested crops were compressed to bales of dimensions 1.0 × 1.2 m (radius × height; Figure 1(a)). The bales were air dried for a period of a month or more in order to reduce the initial moisture content to around 15%. Generally, the economic efficiency of biomass production is highly dependent on the density of the product according to the requirements for transportation, storage, and power for each processing machine. A two-step comminution process, comprising chipping and comminution, was carried out. A chipper machine (Figure 1(b)) was used to cut a miscanthus bale into chipped miscanthus of length 4 to 40 cm (Figure 1(c)). Further, the chipped miscanthus was air dried until its moisture content reached around 5% (±2%); this was the initial moisture content for the experiment.

To comminute previously chipped miscanthus, as shown in Figure 2(a), a hammer mill (Sunbrand, Inc., DamYang, Korea) with power capacity of 30 HP was used (Figure 2(b)). The size of comminuted miscanthus (Figure 2(c)) varied from 1 to 5 mm.

Controlling the moisture content

A simple closed chamber method was devised to control the moisture content of the comminuted miscanthus. A

(a) (b) (c) (d)

Figure 3. (a) The interior of a closed chamber, (b) control panel of the closed chamber, (c) comminuted miscanthus on a precision weigher, and (d) real-time monitoring software.

humidifier was installed in a closed chamber, as shown in Figure 3(a), to supply a given amount of moisture to materials. The temperature of the closed chamber was maintained at 22 to 25°C using a control panel (Figure 3(b)) attached outside (Mani et al., 2004) to simulate moisture exchange under the ambient condition. A precision weigher (resolution = 0.01 g) was placed on the table at a height of 1 m from the bottom of the chamber. This device (Figure 3(c)) concurrently transmitted the measured weight to a data logging software at a sampling frequency of 1 Hz through the digital communication protocol RS-232. The data logging software (Figure 3(d)) had been developed to concurrently monitor the moisture content of the comminuted miscanthus based on the transmitted weight of the sample. The initial weight of the sample was 5 g with approximately 5% of moisture content, as previously stated. As long as the moisture content was under ±2%, the material was stored without providing any additional moisture by a humidifier. Conditioning was repeatedly performed until five different levels of moisture content were obtained by increasing the content by 5% from the previous level. Thus, conditioned samples (six for each moisture content level) were prepared with 5, 10, 15, 20, 25 and 30% of moisture content (each individual was under the range of ±2%). To validate the estimation model after calibration, six more samples for each moisture content level were prepared by same method.

An initiative hypothesis for moisture content measurement

A non-destructive measurement method for moisture content was devised based on image processing. Hypothetically, the moisture content between the comminuted particles and protruded surfaces forms with downward surface curvature was low owing to the attractive forces between those surfaces. Downward surface acts as a dispersive mirror against projected light. Consequently, reflected light is dispersed away from the direction angle of projection, as shown in Figure 4(a). Accordingly, the histogram intensity level for an image captured from the same direction is higher when the inclination of the projected light is smaller. Further, if the highest intensity value called a histogram peak is solely derived from the reflected light, the position of the peak may be biased to a lower level (i.e., to the left in a general histogram plot). On the contrary, for a relatively higher moisture content, the moisture between comminuted particles and protruded surfaces reflects the inclined projection light with much smaller dispersion from the direction of projection, as shown in Figure 4(b), resulting in a contrasting sequence.

Based upon the above hypothesis, a correlation analysis

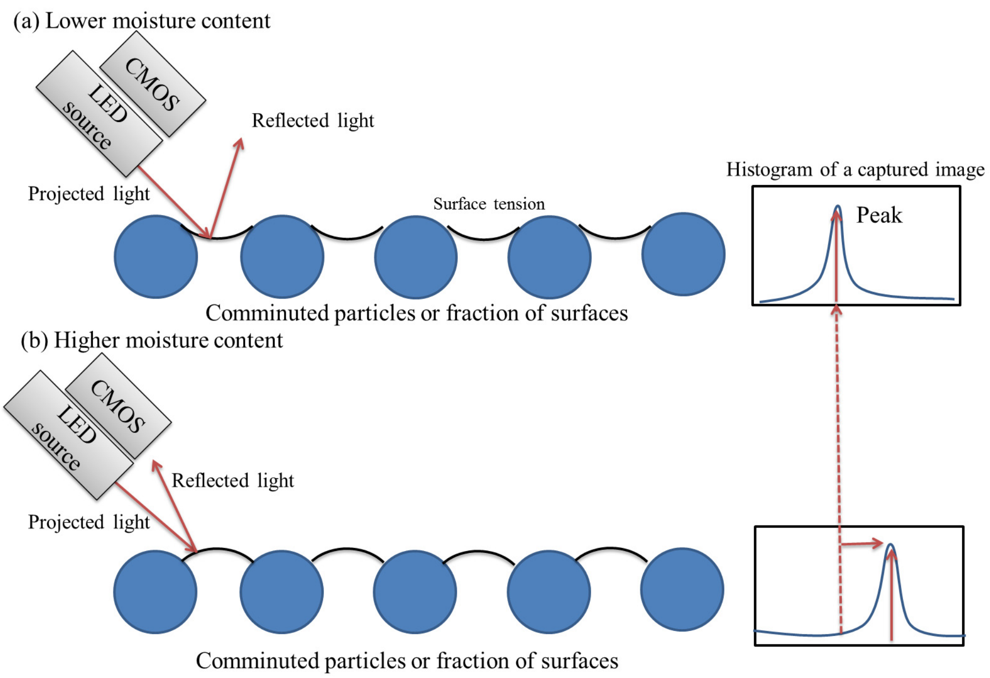

Figure 4. An illustration of the quantification method of moisture content in comminuted particles for relatively (a) lower and (b) higher moisture content.

between moisture content and the intensity levels of reflected light and of the histogram peak was performed using MATLAB (Version 4.a, MathWorks, Inc., MA, USA). For the correlation analysis between the moisture content and intensity level of reflected light, the linear correlation analysis across the full range (0 to 255) of intensity levels was performed to identify the most convincing intensity level associated with the reflected light.

Experimental design

Each sample conditioned for six levels of moisture content (Figure 5(a)) was placed on a white plate. Generally, the ambient brightness of indoor environments (e.g., office and laboratory) without any external projection of light is almost 320 to 520 lux. In order to obtain uniform ambient luminance, the light intensity from the LED source was fixed at around 600 lux. A microscopic-image-capturing device (Figure 5(b)) with projection light of default brightness around 600 lux was located on the upper side about 1 cm away from the target materials. The specifications of this device are listed in Table 2. A magnified image captured by the device is 640 × 480 pixels, as shown in Figure 5(c). The inclination angle of the projection light from the device on the target materials was 45°.

Given that a grayscale image not only is correlated with a 3 band (R, G, B) linear composition, but also carries only intensity information (Johnson, 2006), only the grayscale information obtained from the magnified image was considered in this research.

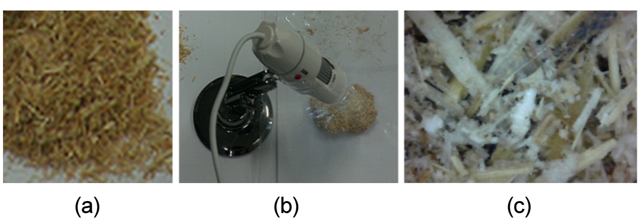

Figure 5. (a) Comminuted miscanthus with conditioned moisture content; (b) capturing a surface image with the projection light; and (c) a magnified image with 640 × 480 pixels.

Table 2. Specifications of the microscopic-image-capturing device

Descriptions	Specifications
Magnification	50×
Capture Resolution	640 × 480
Default Brightness of the Projection LED	around 600 LUX
Weight	380 g
Digital Zoom	5× Sequence Mode
Data transmission and power	USB bulk transfer with 5 V DC

Results and Discussion

Relationship between moisture content and level of histogram peak

Each magnified image captured from a random sample group shown in Figure 6 corresponded to the conditioned moisture content of comminuted miscanthus. By visual inspection, estimating moisture content is invalid.

The histograms shown in Figure 7 have relatively clear peaks for 10, 15, 20, and 25% moisture content. In the case of moisture contents of 5 and 30%, clear peaks can

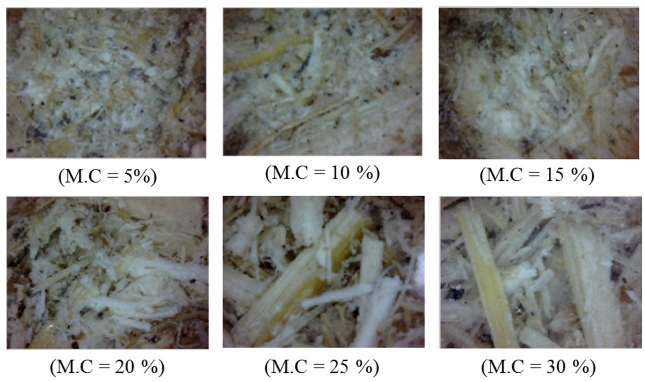

Figure 6. Magnified images of comminuted miscanthus (sample group 1 by random sampling).

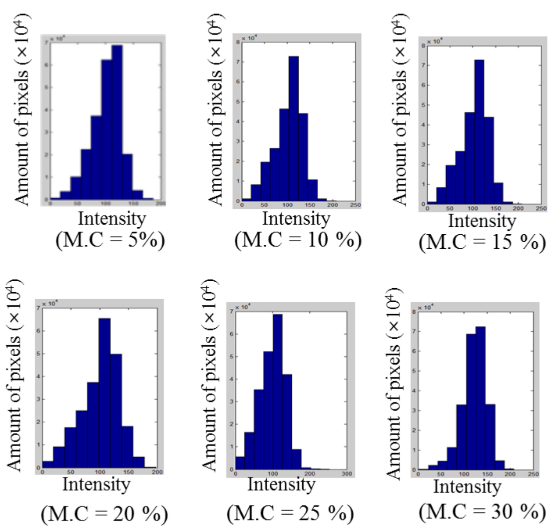

Figure 7. Histograms of the magnified image of comminuted miscanthus (sample group 1 by random sampling) corresponding to its moisture content.

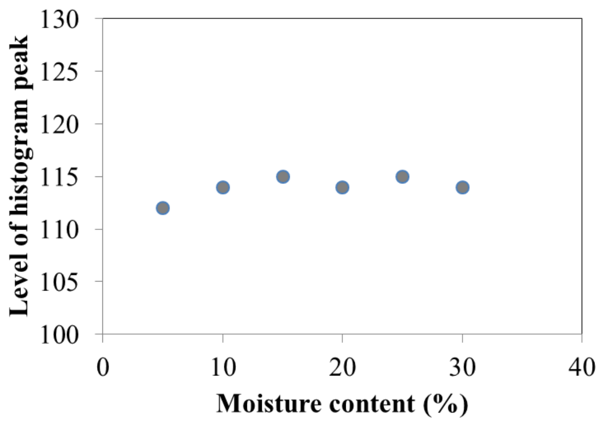

Figure 8. A cross-plot between moisture content and level of histogram peak.

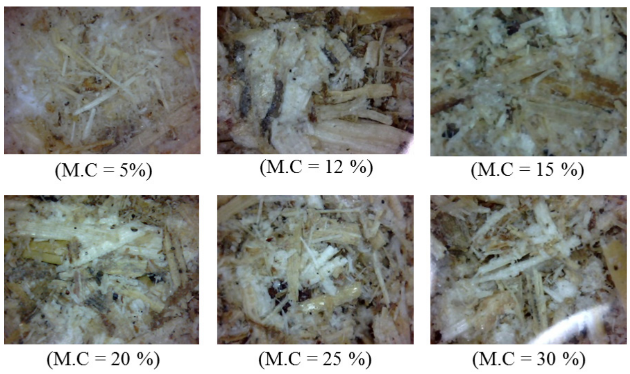

Figure 9. Magnified images of comminuted miscanthus (sample group 2 by random sampling).

be barely seen. An initiative regression analysis was attempted by generating a cross-plot between the moisture content and the level of histogram peak, as shown in Figure 8. This plot shows the lack of a significant relationship between the moisture content and the level of the histogram peak.

Relationship between moisture content and intensity value of histogram peak

As previously observed, the relationship between the moisture content and the level of histogram peak contradicts the initiative hypothesis of this research, which suggested that there might have been a strong relationship between moisture content and a certain intensity level of reflected light. To clarify the extent to which the hypothesis was contradicted, another random sample was grouped for assessment. A cross-plot between the moisture content and the intensity value of the histogram peak revealed a similar contradiction of the hypothesis, as shown in

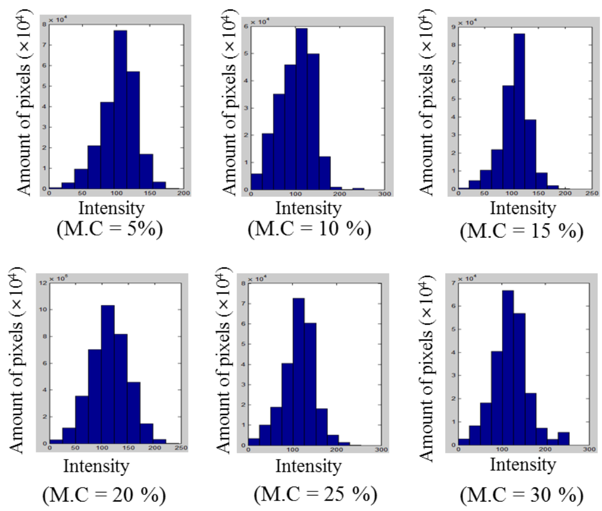

Figure 10. Histograms for the magnified image of comminuted miscanthus (sample group 1 by random sampling) corresponding to its moisture content.

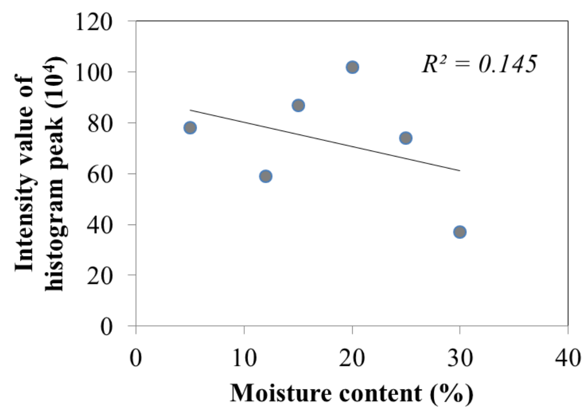

Figure 11. A cross-plot between moisture content and the intensity value of histogram peak.

Figure 11.

While both previous approaches yielded insignificant relationship, a noticeable result was observed. Regardless of the moisture content, the histogram peaks for all 36 samples were consistently found at around 112 (±6) of intensity level as shown in Figure 12. Based on this observation, the hypothesis was revised, and both the level and intensity value of histogram peak were not considered during calibration modeling.

Calibration modeling for moisture content estimation

To find the intensity level most related to the moisture content, iterative linear regression analysis was performed across the full range (0 to 255). Low significance level

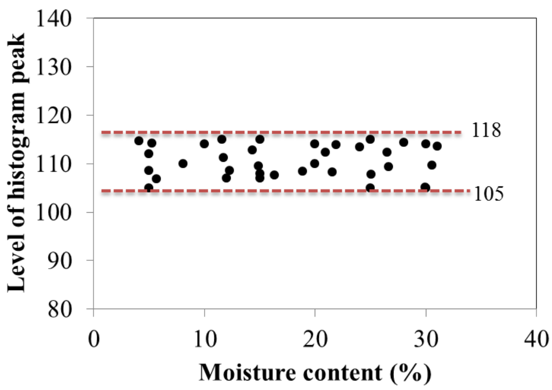

Figure 12. A cross-plot between the moisture content and level of histogram peak for all 36 samples.

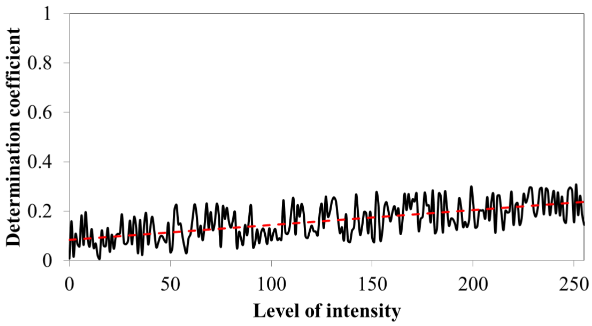

Figure 13. The plot of determination coefficient corresponding to the level of intensity by linear regression analysis.

(<0.31, n = 36) was observed over the entire range of intensity level, as shown in Figure 13. Investigation of the unsatisfactory observation showed a slight increase (a red dotted line in Figure 13) in the determination coefficient through the whole range of intensity level.

Based on the previous unsuccessful approaches, the insignificant relationship between moisture content and one level of intensity (histogram peak or not) was identified. However, based on two noticeable results—namely, an almost consistent histogram peak and a slight inclination at the higher intensity level—the initial hypothesis was revised. In particular, the amount of the reflected light affected by different moisture content could appear at an overall range from a certain level to higher level (generally called a reverse cumulative histogram). Thus, after revising the hypothesis, a reverse cumulative histogram was generated to assign an independent variable for the regression analysis. The aforementioned iterative linear regression was applied with the level of reverse accumulative intensity.

A significant relationship at a 94% confidence level was found for level 108, as shown in Figure 14. To classify

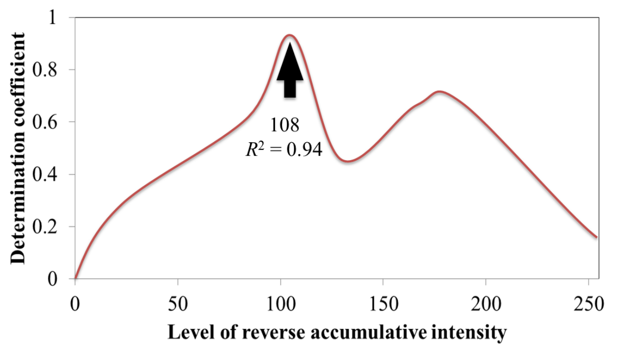

Figure 14. A plot of the determination coefficient corresponding to level of reverse accumulative intensity based on linear regression analysis.

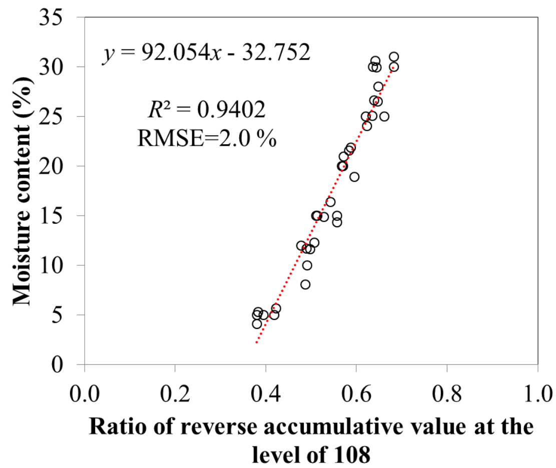

Figure 15. A cross-plot obtained by the linear regression analysis of the ratio of reverse accumulative value and the moisture content of comminuted miscanthus.

the large number of reverse accumulative values at this level as an independent variable for the calibration model, the reverse accumulative value for level 108 was divided by the total summation of the histogram value. Thus, a calibration model with the ratio of the reverse accumulative value as an independent variable and moisture content as a dependent variable was established, as shown in equation 1. The root mean square error (RMSE) of the calibration model was 2.0% (n = 36). Figure 15 shows the cross plot obtained using the calibration model.

$$y = 92.054x - 32.753 \quad (1)$$

where, x is ratio of value at level 108 in reverse accumulative value in a magnified image, and y is the moisture content of comminuted miscanthus.

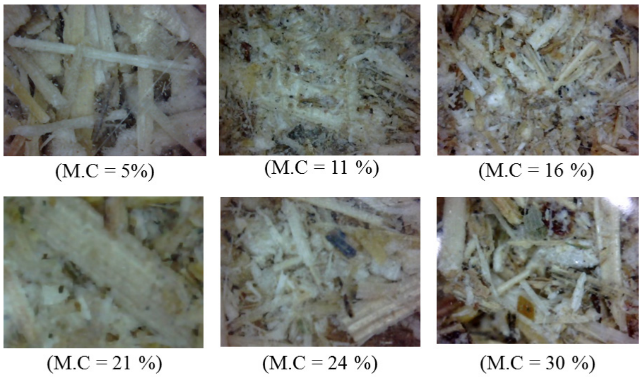

Figure 16. Magnified images of the extra samples used for validation.

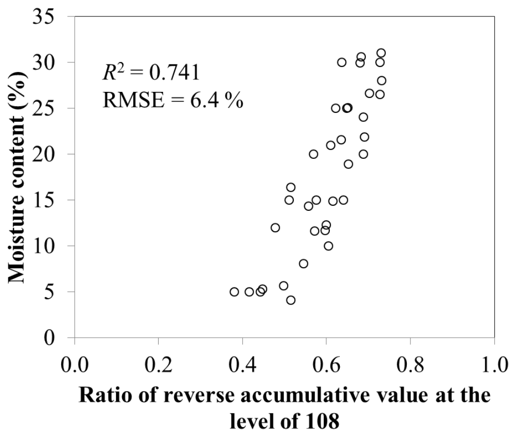

Figure 17. A cross-plot obtained by the estimation model calibrated with the validation samples.

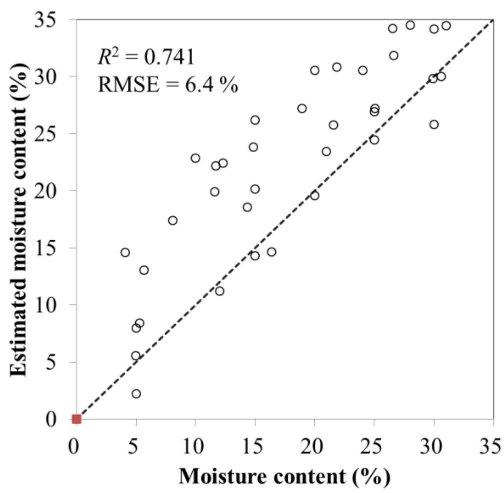

Figure 18. A cross-plot between the conditioned moisture content and the estimated moisture content of the validation samples.

Validation of the estimation model

To validate the calibrated estimation model, the extra samples were tested. Unexpected impurities were found on the comminuted particles in some samples (Figure 16).

The determination coefficient was 0.741 with an RMSE of 6.4% (n = 36) in the validation test. The relationship was relatively less significant than in the case of the calibration model (Figure 17). The validation result showed that the revised hypothesis of this study is valid. In other words, measurement of the intensity of light reflected from finely grinded particles such as comminuted miscanthus may be one of the approaches to the non-destructive and time-efficient estimation of the moisture content of the particles.

Nevertheless, the determination coefficient indicates that the calibration model should compensate for the noise due to various unavoidable defects such as the ambient illumination, impurities, and vibration of the particle holder.

Conclusions

This research explored a hypothesis for developing an estimation model for the moisture content in comminuted miscanthus. Significant relationships between moisture content and the histogram peak or a definitive level of histogram were assumed. Unexpectedly, regression analysis for an initiative hypothesis showed insufficient correlation with low significance (<0.31, n = 36) for the determination coefficient. A revised hypothesis based on a reverse accumulative histogram was proposed. In this case, the relationship was determined to be significant at the 94% confidence level for level 108 in the reverse accumulative histogram. The estimation model was proposed in the form of a linear regression model with the value at level 108 in the reverse accumulative histogram of a magnified image as the independent variable and the moisture content of comminuted miscanthus as the dependent variable. The calibrated linear regression model had a slope of 92.054 and an offset of 32.752 yielded 0.94 for the determination coefficient (RMSE = 0.2%). The validation test showed a significant relationship at the 74% confidence level with an RMSE of 6.4% (n=36). To compensate for the inconsistent significance between the calibration and validation results, an estimation model robust against various systematic interferences is necessary. The economic efficiency of miscanthus, which is one of the most promising energy resources, can be improved by real-time measurement of its crucial material properties.

Conflict of Interest

The authors have no conflicting financial or other interests.

Acknowledgement

This work was supported by the research grant of the Chungbuk National University in 2013.

References

Arabhosseini, A., W. Huisman and J. Müller. 2010. Modeling of the equilibrium moisture content (EMC) of Miscanthus (Miscanthus×giganteus). Biomass and Bioenergy 34: 411-316.

Carr-Brion, K. 1986. Moisture Sensors in Process Control. London and New York: Elsevier Applied Science Publishers.

Consentino, S. L., P. Cristina, S. Emanuele, C. Venera and F. Salvatore. 2007. Effects of soil water content and nitrogen supply on the productivity of Miscanthus× giganteus Greef et Deu. in a Mediterranean environment. Industrial Crops and Products 25:75-88.

Dalton, F. N. and M. Th. Van Genucheten. 1986. The time-domain reflectometry method for measuring soil water content and salinity. Geoderma 38:237-250.

Danalatos, N. G., S. V. Archonotoulis and I. Mitsios. 2006. Potential growth and biomass productivity of Miscanthus giganteus as affected by plant density and N-fertilization in central Greece. Biomass Bioenergy 31(2(3)):145-52.

Johnson, S. 2006. Stephen Johnson on Digital Photography. California: O'Reilly Media.

Kodama, M., S. Kudo and T. Kosuge. 1985. Application of atmospheric neutrons to soil moisture measurement. Soil Sci 140:237-242.

Hess, J. R., K. L. Kenney, L. P. Ovard, E. M. Searcy and C. T. Wright. 2009. Uniform-format solid feedstock supply system: A commodity-scale design to produce an infrastructure-compatible bulk solid from lignocellulosic biomass: Section 4. INL/EXT-08-14752 Revision 0 DRAFT. Idaho national laboratory, Bioenergy Program, Idaho Falls, ID 83415.

Hilhorst, M. A. and C. Dirksen. 1994. Dielectric water content sensors: time domain versus frequency domain. Proc. Symp. TDR Environmental, Infrastructure and Mining Applications: 143-153.

Holt, G. A., T. I. Blodgett and F. S. Nakamura. 2006, Physical and combustion characteristics of pellet fuel from cotton gin by-products produced by select processing treatments. Industrial Crops and Products 24(3):204-213.

Mani, S., L. G. Tabil and S. Sokhansanj. 2004. Grinding performance and physical properties of wheat and barley straws, corn stover and switchgrass. Biomass Bioenergy 27:339-352.

Martin, K. A. 1993. Direct measurement of moisture in skin by NIR spectroscopy. J. Soc. Cosmet. Chem 44: 249-261.

Miao, Z., T. E. Grift, A. C. Hansen and K. C. Ting. 2011. Energy requirement for comminution of biomass in relation to particle physical properties. Industrial Crops and Products 33:504-513.

Sokhansanj, S., A. Kumar and A. F. Turhollow. 2006. Development and implementation of integrated biomass supply analysis and logistics model (IBSAL). Biomass Bioenergy 30:38-847.

Wignerom, J. P., A. Chanzy, J. C. Calvet and N. Bruiguier. 1995. A simple algorithm to retrieve soil moisture and vegetation biomass using passive microwave measurements over crop fields. Remote Sensing of Environment 51(3):331-341.