The residual biomass and environmental security: optimizing agglomeration process

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Abstract. One of the critical approaches to ensure environmental security is to transition away from fossil fuels and focus instead on producing and using biofuels from plant-based waste materials. In this study, the effects of residual biomass on environmental security are elaborated. Moreover, the chemical composition of biomasses is determined to estimate the optimal parameters for the agglomeration process. Thanks to their contribution as alternative energy sources, residual biomass such as crop residues and wood waste are now considered natural byproducts produced in agricultural industries. In this paper, these different biomasses are squeezed in a load cell using a hydraulic piston press under identical manufacturing conditions. The effects of cellulose, lignin, and starch content on various biomass agglomerations are investigated. Results show that in the case of untreated materials, tablets created from biomass materials with lower cellulose content have lower densities and higher spring-back ratios. Tablets made from biomass materials with higher lignin content display greater strength. In the case of treated materials, the chemical composition of biomass changed.
Key Words: biomass, residual biomass, agglomeration, environmental security.

Introduction. In recent years, the environment quality in Vietnam and other countries has been changing in an unfavorable direction for people's lives. Ensuring environmental security has become a concern and is acknowledged to be one of the long-term needs of society as a whole and, thus, the obligation of governments worldwide. According to Law on Environmental Protection No. 55/2014/QH13, environmental security is defined as the assurance that there will be no major impact of the environment on the political, social stability and economic development of a country. To ensure environmental security, actions are required, including minimizing or preventing environmental pollution and reducing emissions of CO_2, dust, and toxic substances into the air environment.

Benová et al (2021) studied the energy utilization of residual biomass seems to be an optimal solution for sustainable waste management and enhancing the country’s energy security via local and renewable sources. General biomasses provide an alternative energy source that can potentially and significantly replace the role of fossil fuels. The world's increasing population and depleted fossil fuel reserves necessitate finding alternative energy options and sustainable technology to produce clean energy. For this reason, many countries in the European Union have increasingly used wood biomass for energy, and consequently, bioenergy is shaping up to be the primary source of renewable energy in that region (IEA 2016). According to the Decision 1264/QD-TTg 2019, the Vietnamese government will give priority to reasonable development of renewable energies.

Biofuels appear in all forms: solid, liquid, and gaseous. Regardless of their condition, the source of residual biomass comes from industries involved in harvesting natural resources for human consumption, e.g., agriculture and forestry (Sims et al 2010, Foust et al 2009). Sudha et al (2021) studied the effects of several conditions on algal biomass and biofuel production. Other studies focus on optimizing the power generation of densified sawdust, shavings, and other particulate biomass materials (Kathuria 2012; Gebresas et al 2015; Kyauta et al 2015; Henriksson et al 2019). Shaping and compactifying biomass via briquette, extrusion, tabletting, and pelletizing can, aside from improving its quality, facilitate more convenient storage by increasing its density, thereby making the handling easier and reducing transportation costs. The densification of biomass sources with varying chemical compositions necessitates diverse process parameters (Kashaniejad et al 2011; Stelte et al 2011; Samuelsson et al 2012; Stahl et al 2012).

The three organic elements of lignocellulosic biomass (Figure 1) are lignin, cellulose, and hemicellulose. Depending on the source of the biomass and the plant structure from which it was sourced, the exact elemental composition may vary. Due to the presence of connected phenylpropane units, Yu et al (2017) described lignin as a three-dimensional polymer with a random network that is thus sturdy.

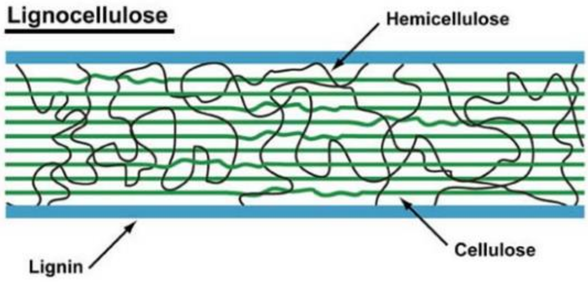

Figure 1. The components of lignocellulosic cellulose.

According to Tran et al (2021), the total rice straw generated in Vietnam is estimated at 53.3 Mt year^{-1}. Around 40% (21 Mt) is used to produce 2,565 MW of electricity per year. The rest is used as cooking fuel, cattle feed, mushroom production, or burned in open fields. Straw biomass burning in Vietnam caused serious air pollution during the burning process, causing haze for many days, and seriously affecting daily life, people's health and the environment, obscuring the view of road users, even threatening aviation safety, and directly threatened the environmental security of Vietnam. Despite widespread domestic use, a significant portion of this agricultural waste remains unutilized. If agricultural residue is not treated. It will pollute the environment, leading to community and social conflicts, thereby affecting the local security situation. In March 2020, the Prime Minister of Vietnam approved Decision No. 08/2020/QD-TTg, which supplements the preceding promulgation (Decision 24, dated 24/3/2014) on the development of biomass power plants in Vietnam. The taxes imposed on power generated using biomass were significantly lowered. The price for biomass-thermal power cogeneration is reduced to 7.03 US cents kWh^{-1}, approximately 17% lower than the generation charge for energy from other biomass sources. Furthermore, in resolution No. 55-NQ/TW 2020, orientation of the National Energy Development Strategy through 2030, the political bureau of the communist party mandated ambitious targets for the energy sector, such as becoming energy self-sufficient by 2030, with 15-20% of this energy supply sourced from renewable sources.

Biomass energy limitations

Environmental harm. Converting waste into something useful requires catalyzing chemical reactions, e.g., combustion. It is, therefore, inevitable to produce unwanted byproducts, like the emission of gases (sulfur dioxide, nitric oxides, methane, etc.) and particulates. Increasing the scale of biomass production may also require the use of chemical fertilizers and pesticides. As such, comprehensive preparations must be in place to minimize environmental damage.

Technical and technological challenges. Renewable energy, though commercially viable in many developed countries, remains underappreciated in Vietnam due to a lack of technical expertise to scale and insufficient knowledge dissemination. Several renewable energy sources, like biomass and solar, maybe climate-dependent. Thus, balancing the dependency between renewable and non-renewable sources poses a challenge, especially in assuring the country with consistent, reliable, and secure electrical resources.

Financial and economic challenges. While renewable energy attracts much attention, most of it focuses on those that use more modern technology, e.g., wind and solar energy. Renewable energy sources from agricultural waste fail to attract significant investments, especially those that will facilitate lasting changes. The promise and usefulness of these techniques must then be further promoted and showcased to garner more financial resources for development.

The theoretical background of the compressibility factor of the tablet. The equation of Johanson (1965) can take two forms:

$$\frac{\rho}{\rho^*} = \left(\frac{p}{P^*}\right)^{1/\kappa}$$

$$\frac{F}{F_0} = \left(\frac{V_0}{V}\right)^{\kappa}$$

Where:
κ - compressibility factor;
ρ - agglomerate density;
p - tabletting pressure;
F - tabletting force;
V - tablet volume;
p*, ρ*, F_o, V_o - reference values (if the surface perpendicular to force and mass of the tablet are constant).

The new compression equation was introduced by Trinh et al (2017), which contains moisture content as a parameter and updates the Johanson model:

$$\rho = (7.763m + 201.724).P^{(-0.0067m + 0.2995)}$$

Where:
m - moisture content (wt.%);
P - applied pressure (MPa);
ρ - density (kg m^{-3}).

In a recent study, Trinh et al (2020) reported a formula to measure relative radial pressure relative position points:

$$\frac{P_R}{P_{R_0}} = 1 - c\left(\frac{x}{x_c}\right)^d$$

Where:
P_{R_0}- initial radial pressure;
c - constant;
d - exponent,
$\frac{x}{x_c}$ - a relative position.

Optimizing agglomeration process, novelty. Biomass agglomeration is required to increase the efficiency in generating biofuel for household and industrial use. Although many researchers have found optimal parameters for parts of the agglomeration process, e.g., moisture content, temperature, and particle size, no existing research in the literature assess the effect of lignin, cellulose, and starch content on the strength and density of various biomass tablets. Moreover, the current work aims to supplement the analysis of the advantages of biomass energy, as well as analyze its limitations in terms of environmental risk, availability of technology and economic challenges.

The chemical composition of biomass affects the agglomeration process. For efficient use of biomass, agglomeration is essential. However, many parameters influence the agglomeration process. In our previous studies, the effects of temperature, moisture content, particle size, and compression time on the agglomeration process were determined to find optimal parameters. In this study, the focus is on studying the effect of biomass composition on the agglomeration process.

Material and Method

Biomasses (including spelt chaff raw material, beech sawdust, *Acacia mangium* one-month seasoned wood sawdust, and rice straw) were used for the experiments.

Spelt chaff and ground post-agglomerated spelt chaff. Spelt chaff raw material originated from Szendrő, Hungary (Natur Gold Farms Ltd.). It was dried and then grounded using a cutting mill (Retsch SM2000) in a single step (screen size of 2 mm). This material had a particle size of (x)<1.6 mm, a bulk density of 193 kg m^{-3} and a moisture content of 5.3 wt%. Figure 2 (left) shows a sample of the raw material of spelt chaff. Spelt chaff is a homogeneous material with a consistent particle shape and an elongated form. Ground post-agglomerated (GPA) spelt chaff, the feed material was produced from agglomeration spelt chaff raw material at a temperature of 100°C (x<1.6 mm) and then ground at screen size 2 mm. This material has particle size <1.6 mm and a bulk density of 354 kg m^{-3} at a moisture content of 5 wt%. Figure 2 (right) shows the GPA-spelt chaff. It can be seen that the GPA-spelt chaff is an inhomogeneous material with irregularly shaped particles of spheroid and elongated form.

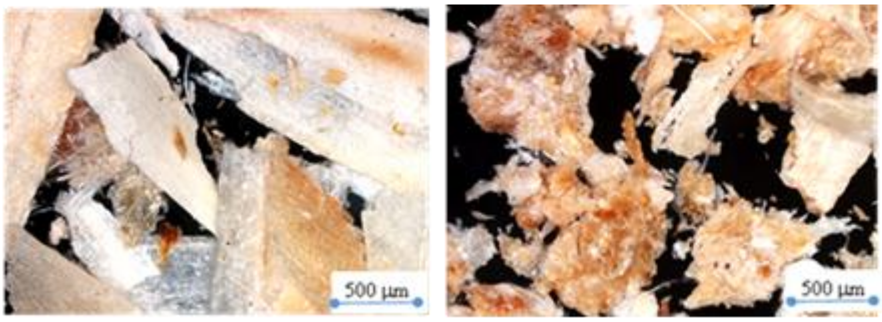

Figure 2. Spelt chaff raw material (left) and GPA- spelt chaff (right). (The optical microscope used: Zeiss AXIO Imager M2m.)

Beech sawdust. Beech sawdust originated from Miskolc, Hungary (Borsodwood Ltd.). It was dried and then grounded using a cutting mill (screen size of 2 mm). The moisture contents and bulk density of beech biomass were calculated as 1.44 wt%, 252 kg m^{-3} (x<1.6 mm). The raw material of beech sawdust can be seen in Figure 3. Beech sawdust is visibly a homogeneous material and a regularly shaped particle with a rectangular prism form.

Figure 3. Beech sawdust optical microscope.

Acacia mangium sawdust. An 8-year-old *A. mangium* was obtained from the Quang Ninh province, Vietnam. Half of it was seasoned for one month by being covered outdoors, while the other half was seasoned for six months in Vietnam. In the case of one-month seasoned wood was comminuted by a cutting mill in one step (screen size 2 mm). The moisture contents and bulk density of *A. mangium* biomass were calculated as 5.3 wt% and 133 kg m^{-3} (x<1.6 mm) respectively. Figure 4 (left) shows *A. mangium* sawdust. It can be seen that *A. mangium* sawdust of one-month seasoned wood is a homogeneous material with regularly shaped particles of an elongated form. The six months of seasoned wood was comminuted by a cutting mill in a single step (screen size of 2 mm). The moisture content (MC) and bulk density of *A. mangium* sawdust were 5.1 wt% and 204 kg m^{-3} with particle size <1.6 mm. Raw material *A. mangium* sawdust can be seen in Figure 4 (right). Similar to beech sawdust, *A. mangium* sawdust from six months- seasoned wood is a homogeneous material with regularly shaped particles of an elongated form.

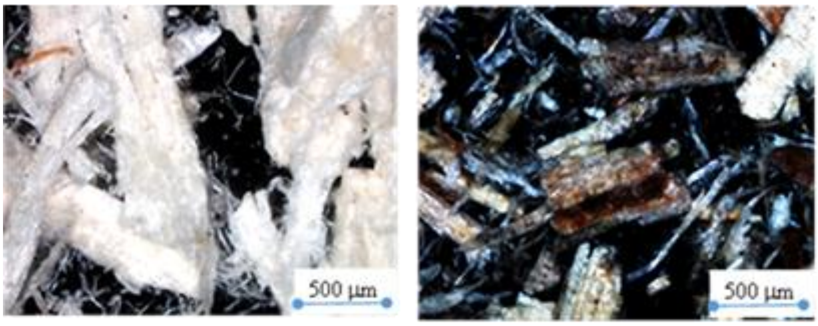

Figure 4. *Acacia mangium* sawdust: one-month seasoned wood (left), six months seasoned wood (right). Optical microscope.

Rice straw. Rice straw originated from Nam Dinh province, Vietnam. It was comminuted by using a cutting mill in a single step (screen size of 2 mm). The moisture content, bulk density, and particle size were calculated as 5 wt.%, 224 kg m^{-3}, and x<1.6 mm respectively. Figure 5 shows the rice straw. It can be seen that rice straw is an inhomogeneous material, with regularly shaped particles of an elongated form.

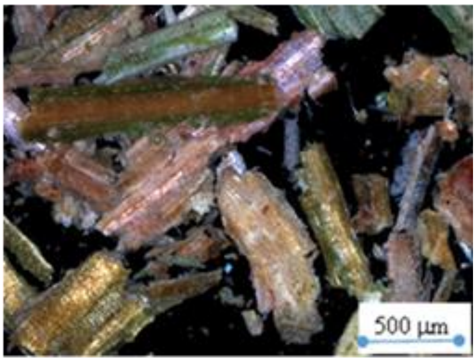

Figure 5. Rice straw optical microscope.

Hydraulic piston press. Figure 6 shows the hydraulic piston press used in our experiment at the University of Miskolc. The following are the machine's parameters: a maximum force of 200 kN, a maximum velocity of the piston at 30 mm s^{-1}, and the piston position can be measured by an incremental encoder in a heat-cable load cell (20-140°C).


Figure 6. Hydraulic piston press.

Procedure of the experiment. Chemical analysis of six different types of biomasses was performed at Mezőlabor - Szolgáltató és Kereskedelmi Kft, Hungary. The amount of ADF (Acid Detergent Fiber), ADL (Acid Detergent Lignin), and starch were measured. In this way, lignin content is determined as ADL (in the case of a small amount of cutin), and cellulose can be calculated as ADF - ADL. In this experiment, the 25 mm diameter piston press was used, and a tablet was prepared with 3 g of material. Pressures applied ranged from 50 to 300 MPa on the surface of tablets, under the same production conditions (x<1.6 mm, the temperature of 100°C, moisture content of 5% weight, and the compression time of two seconds). The volume and mass of the tablet calculated the density of each tablet. The shortest height of tablets was measured by an incremental encoder. According to Dhamodaran & Afzal (2012), the expansion in the axial and/or radial dimensions of a compacted granular/powder material when the applied pressure is removed is called the spring-back effect. The spring back ratio (SBR) of a tablet can be calculated by using the below formula.

$$\mathrm{SBR\%} = \frac{\mathrm{H_t} - \mathrm{H_{tp}}}{\mathrm{H_{tp}}} \cdot 100$$

Where:
H_t - the tablet's maximum height;
H_{tp} - the shortest height of the tablet under pressure.

The fall test method was used to determine the tablet's strength. Each tablet was repeatedly dropped from a height of 2 m onto a concrete floor until it breaks apart into pieces. The falling number was determined by counting the number of falls the sample survived unharmed. Each reported measurement was based on a three-experiment average. The particle shape of different raw materials was visualized using an optical microscope Zeiss AXIO M2m Imager.

Results and Discussion

Lignin, cellulose, and starch content determination. Table 1 shows the composition of biomasses concerning the three main components: lignin, cellulose, and starch. In all biomass samples, cellulose is substantially more present than lignin. Compared to other raw materials, GPA-spelt chaff has the most amount of starch and the lowest lignin content. Lignin content varied from 3.9 to 26.6%, whereas cellulose ranged between 25.1 and 52.1%.

Table 1

Lignin, cellulose, starch content and particle density of biomass materials

Components	*Materials*					
	Untreated				*Treated*	
	Beech	*A. mangium 1 month*	*Rice straw*	*Spelt chaff*	*GPA-spelt chaff*	*A. mangium 6 months*
Lignin (%)	15.4	26.6	4.7	8.8	3.9	23.7
Cellulose (%)	52.1	47.4	41.9	35.1	25.1	51.2
Starch (%)	<0.5	<0.5	<0.54	<0.5	9.3	<0.5

After six months of preparation, seasoned *A. mangium* wood displayed a reduction of lignin and increased cellulose composition, but with starch content essentially unchanged. The rationale is that several treatment procedures for biomass materials are currently accessible, with temperature, catalyst type, and treatment period variations. These differences have an impact on the severity of the treated biomass as well as the content of the biomass as it degrades (Pedersen & Meyer 2010). In-ground post-agglomerated spelt chaff, there was a decrease in lignin and cellulose content and an increase in starch content. This is because the heating material can release glucose from cellulose and lignin, while starch is proportionate to glucose (Kayisu et al 1885).

The density of residual biomass tablets. Residual biomass tablets were compressed using a hydraulic piston press using the same amount of pressure for all materials (see Figure 7), and the average tablet density was calculated. Figure 8 shows that the final density increases with the pressure, according to the best-fit Johanson curves. The coefficient of determination (R^2), the residual mean square (σ), and the spread deviation values (V_s) of fitted equations are calculated for all samples and values (V_s) less than 4.4%, in the case of GPA-spelt chaff (V_s = 1.3%).

The density of biomass tablets increases with the squeezing pressure. Under similar production conditions, beech sawdust tablets displayed the highest density values, while those made from *A. mangium* six-month seasoned wood are the least dense. Biomass tablets composed of ground post-agglomeration spelt chaff are denser than those made from spelt chaff. Lastly, one-month seasoned *A. mangium* wood tablets have a higher density than those made from six months-seasoned wood.

Figure 7. Biomass tablets are produced from different raw materials and under different pressures.

To illustrate the above, we give some specific values, for instance, when the pressure applied is 200 MPa. As can be seen from Figure 8, the tablets densities for different materials are as follows (in decreasing densities): beech sawdust (1,341 kg m^{-3}), ground post-agglomerated spelt chaff (1,238 kg m^{-3}), *A. mangium* one-month seasoned wood (1,136 kg m^{-3}), rice straw (1,120 kg m^{-3}), spelt chaff (1,058 kg m^{-3}) and *A. mangium* six-month seasoned wood (904 kg m^{-3}).

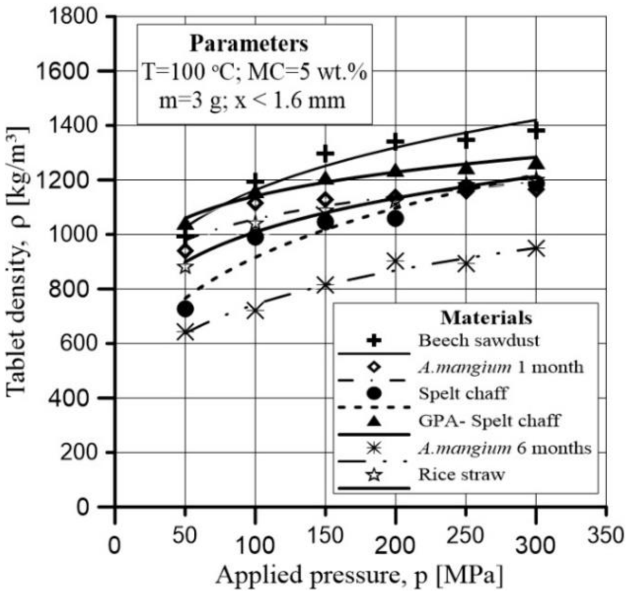

Figure 8. Density as a function of applied pressure for various materials.

Table 2

Johanson's equation constants ($\rho = a p^{1/\kappa}$) for diverse materials

Type of material	*Constant a* $[kg^{1-1/\kappa} m^{(1/\kappa)-3} s^{2/\kappa}]$	*Constant κ [-]*	*Spread deviation: V_s [%] Coefficient of determination: R^2 [-] Residual mean square: σ [kg m^{-3}]*
Beech sawdust	503.1176	5.5006	V_s=2.9; R^2=0.9404; σ=0.0011
A. mangium 1 month	636.6259	9.0992	V_s=3.1; R^2=0.8284; σ=0.0013
A. mangium 6 months	265.0771	4.4683	V_s=2.5; R^2=0.9715; σ=0.0008
Spelt chaff	276.8775	3.8489	V_s=4.4; R^2=0.9280; σ=0.0028
GPA- spelt chaff	695.6108	9.3197	V_s=1.3; R^2=0.9621; σ=0.0002
Rice straw	466.4309	5.9701	V_s=1.6; R^2=0.9744; =0.0004

Cellulose content could be the main factor affecting the density of the produced tablets, since, as seen in Figure 9, materials with more cellulose display larger compressibility. Indeed, lower cellulose content is associated with tablet porosity (Harmsen 2010; Karimi et al 2013), thereby, more air pockets occupy volume when uncompressed. Treated materials, seasoned longer or ground post-agglomeration, have higher cellulose content than their untreated counterparts and are likewise denser. The densities of wheat starch are 1.6 g m^{-3} for dry granules, 1.5 g m^{-3} for air equilibrated granules (Dengate et al 1978). Cellulose with amorphous or crystalline structures has a density between 1,500 and 1,588 kg m^{-3} (Yang 2008), while that of lignin ranges from 1348 to 1451 kg m^{-3} (Jiang 2001).

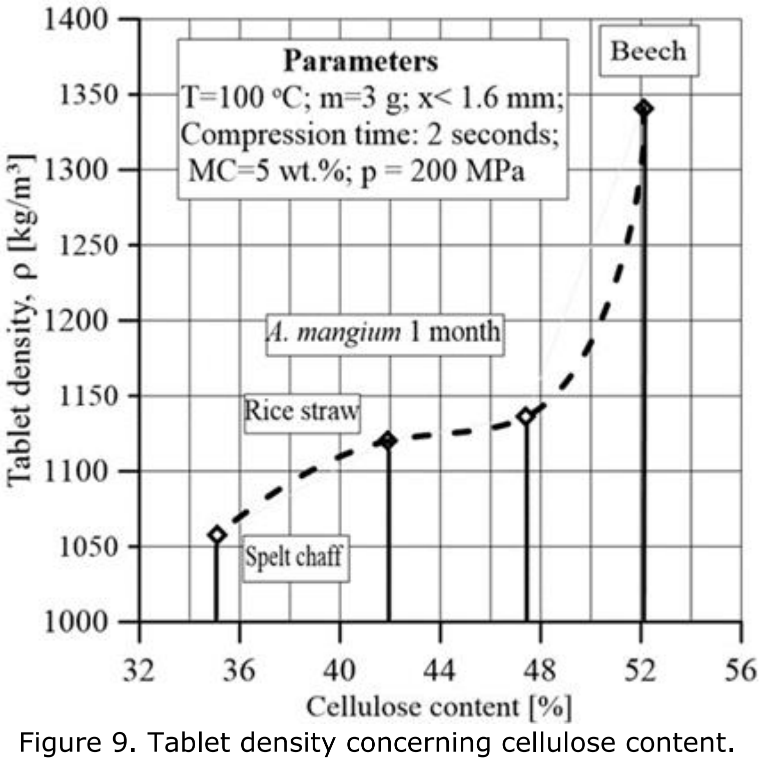

Figure 9. Tablet density concerning cellulose content.

Springback ratio (SBR). Under the same production conditions (2-second compression time at 100°C, 5 wt% moisture content, sample weight 3 g, and particle size less than 1.6 mm), the spring back ratio (SBR) is calculated for different materials (Figure 10). For instance, the following are the SBR for different materials: rice straw (37.2%), spelt chaff (35%), *A. mangium* six months-seasoned wood (30%), *A. mangium* one month-seasoned wood (22%), beech sawdust (16%) and GPA-spelt chaff (14%). As illustrated, the SBR of tablets prepared with GPA-spelt chaff displayed the lowest values while the rice straw tablets have the highest SBR. Unlike other materials where the SBR decreases with the applied pressure, the SBR of tablets made from *A. mangium* one month-seasoned wood increases with the pressure.

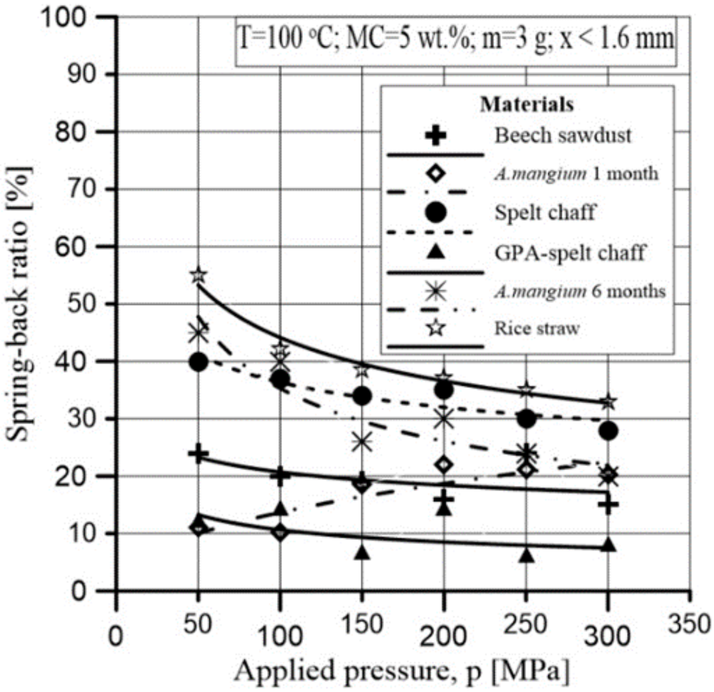

Figure 10. Springback ratio of biomass tablets made from various materials.

Residual biomass tablet strength. The falling number measures biomass tablet integrity. Figure 11 shows falling number values for tablets formed from different materials under identical production conditions. Among the untreated materials, tablets made from one-month seasoned *A. mangium* wood have the highest falling number, while the rice straw tablets have the lowest one. Among treated materials, the falling number of six-month seasoned *A. mangium* tablets was significantly lower than the GPA-spelt chaff tablets. As an illustration, the mean falling numbers at 200 MPa are as follows: 20.3 (one-month seasoned *A. mangium* wood), 8.0 (beech sawdust), 7.3 (GPA-spelt chaff), 3.0 (spelt chaff), 2.3 (rice straw), 1.3 (six-months seasoned *A. mangium* wood).

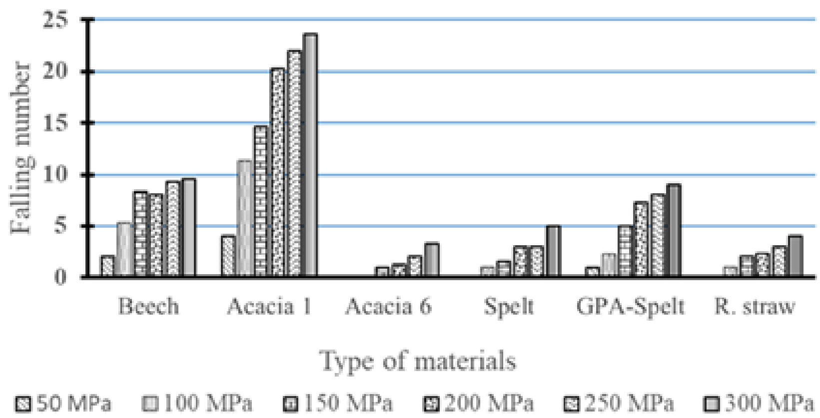

Figure 11. The falling number of biomass tablets is created from various materials and at different pressures.

Figure 12 shows the falling number values and lignin content of tablets in the case of untreated materials but with similar starch content. The lignin acts as adhesive (Dai et al 2017), which could well explain why materials with higher lignin content display more structural integrity. For treated materials, higher starch content characterizes stronger tablets. Indeed, starch is a naturally-occurring binding agent and its presence results in stronger resistance to abrasion (Stahl et al 2012).

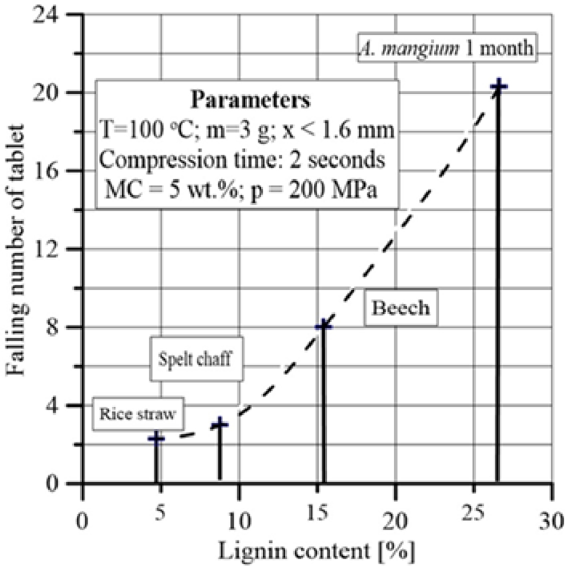

Figure 12. Relationship between lignin content and falling number of biomass tablets.

Conclusions. For residual biomass tablets made of untreated materials (beech sawdust, spelt chaff, one-month seasoned *A. mangium* wood, and rice straw) cellulose content is the determining factor: reduced cellulose values are translated into lower densities and higher spring back ratios. With identical starch composition, tablets manufactured from lignin-rich materials exhibited higher strength. Rice straw tablets with a low lignin content (4.7%) have smaller granules, are smoother, have smaller pores, and have higher densities than those made from spelt chaff. In the case of treated materials, the residual biomass component ratios changed. For example, spelt chaff's cellulose and lignin content decreased when simultaneously subjected to heat, then compressed and ground again (GPA spelt chaff). The starch content was higher than the spelt chaff raw material (9.3% vs 0.5%). The biomass tablets made from material with more starch are denser, smoother and have lower spring-back ratios. The effect of other components of residual biomass (for example hemicellulose, proteins, lipid, and fat) on the structural properties of the resulting tablets is reserved for future studies. The results of this experimental research have some implications for those technologists and innovative business managers in developing countries like Vietnam to continue investing in research and development activities in order to create value from agricultural and industrial wastes that can be processed into renewable materials or biofuel raw materials for a raw materials sustainable management, and thus making contributions to the course of ensuring environmental security for humans.

Acknowledgements. The authors greatly appreciate the help of Assoc. Prof. Sándor Nagy and Prof. Barnabás Csőke for the valuable comments and suggestions. We thank Emanuel Plan for providing language assistance.

Conflict of interest. The authors declare no conflict of interest.

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Received: 30 January 2023. Accepted: 11 March 2023. Published online: 25 March 2023.
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How to cite this article:
Trinh Q. V., Hoang T. A., Do H. K., Do T. C., 2023 The residual biomass and environmental security: optimizing agglomeration process. AAB Bioflux 15(1):1-12.