



Agglomeration of Biomass Feedstocks for Bioenergy Applications

**A Final Report Submitted to
The Southeastern Sun Grant Center**

Submitted by

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EXECUTIVE SUMMARY

Biomass feedstocks (especially the lignocellulosic biomass type) are crucial to a more sustainable energy future in U.S. because it is the only renewable source for carbon-based fuels and chemicals. One of the major bottlenecks that has impeded the commercialization of biomass to bioenergy plants is the high cost of transporting biomass (due to typical low density of biomass) from place of generation/production to bioenergy plants. This project investigated the minimum pressure/moisture content that will produce stable compacts from four biomass feedstocks – poultry litter, switchgrass, peanut hull and pine wood. Results obtained indicated that compacts can be produced from these biomass feedstocks at pressures significantly lower (four to ten orders of magnitude) than those required for pelleting and cubing.

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Abstract

Biomass feedstocks (especially the lignocellulosic biomass type) are crucial to a more sustainable energy future in U.S. because it is the only renewable source for carbon-based fuels and chemicals. One of the major bottlenecks that has impeded the commercialization of biomass to bioenergy plants is the high cost of transporting biomass (due to typical low density of biomass) from place of generation/production to bioenergy plants. This project investigated the minimum pressure/moisture content that will produce stable compacts from four biomass feedstocks – poultry litter, switchgrass, peanut hull and pine wood. Results obtained indicated that addition of moisture significantly improved the stability of poultry litter compacts. Stable compacts were obtained from poultry litter samples adjusted to moisture content of 37.7% and compacted at a pressure of 5.0 MPa. Addition of moisture had a negative effect on switchgrass, peanut hull and pine wood compaction. Stable compacts were obtained from switchgrass and pine wood at a pressure of 17.3 MPa and moisture content of about 8.0%.

PROBLEM

Biomass feedstocks are lightly densed ($<150 \text{ kg/m}^3$, Sokhansanj and Turhollow, 2004) and therefore cannot be efficiently and economically transported over long distances (usually > 10 miles) to areas where they can be effectively converted into bioenergy, biofuels and bioproducts. Some form of agglomeration or densification is therefore needed for easier handling, storage and transportation of biomass feedstocks. Pelletization (pressure-type agglomeration method) is often used to compact agricultural materials because of (a) its applicability to virtually any biological material, (b) comparatively high density of pelleted material (four to six fold over original material's density), and (c) pellets can be handled efficiently using traditional bulk handling equipment (Fasina and Sokhansanj, 1996). Pellets are obtained by grinding, conditioning and then extruding the ground materials through 4-12 mm cylindrical dies (McMullen et al., 2005). Several studies (Colley et al., 2005; Tabil and Sokhansanj, 1996) have shown that the energy to pelletize biomass feedstocks can be as high as 100 MJ/t. This high energy requirement for pelleting is a major contributor to the cost-prohibitive application of pelleting to low-value biomass feedstocks.

Cubing is another type of pressure agglomeration that has been applied primarily to forage crops. The cubing operation increases material density on the order of three to five fold. Cubes produced from this unit operation can also be handled by conventional bulk handling equipment. Cost analyses by Sokhansanj and Turhollow (2004) and Mani et al. (2006) indicated that cubing is cheaper than pelleting. This cost reduction is partly due to lower pressures required for cubing and the lesser amount of unit operations that is carried out on the raw material before agglomeration in comparison to pelleting (e.g. cubes are typically manufactured from chopped alfalfa while alfalfa has to be ground prior to pelletizing). Adapa et al. (2005) studied the cubing characteristics of fractionated sun-cured and dehydrated alfalfa chops and found that cube hardness and density increased with applied pressure, residence time and cube temperature. However, the authors did not document the amount of energy required for cubing. In addition, no documented study exists on the cubing characteristics of biomass feedstocks.

One of the major drawbacks of both the pelleting and cubing operations is that the feedstock, to be agglomerated, must still be transported to a central processing site. This procedure partially defeats the main goal for agglomerating the material especially in the case of processing low-value biomass. In addition, there may be biosecurity issues with transportation of raw/unagglomerated agricultural wastes/residue from the place of generation. For example, poultry litter is a potential biomass in the poultry producing region of the country. Poultry litter however is dusty and known to contain pathogens such as *E. Coli* (Nandi et al., 2004). During transportation, pathogen infected dust may be released into the atmosphere. This biosecurity issue could lead to the spreading of poultry-related diseases within regions that litter is transported through. This problem could be considerably minimized if the poultry litter is densified on-farm because this would reduce the dispersion of dust and dust-laden microbes during transportation (Fasina et al., 2006). A preliminary study at Auburn University (Fasina et al., 2006) demonstrated that cube-like material (herein called compacts) can be produced from poultry litter at very high moisture contents (>25%, w.b.) (Figure 1). There is therefore the need to develop agglomeration methods that can be implemented at the farm level/generation sites. This implementation will however require fundamental studies on the agglomeration of biomass feedstocks at low pressures.

Therefore, the overall objective of this project was to develop farm-level, low-pressure methods for agglomerating biomass feedstocks that are indigenous to the southeastern part of the

United States into forms (cubes/compacts) that are suitable for economical and efficient handling, storage and transportation of biomass. The success of this proposed research will enhance America's energy security, provide American's agriculture diversification and environmental sustainability, and promote opportunities for economic diversification in American's rural communities. To meet the overall project goal, the specific objectives of the research are to investigate the:

- (a) Effects of moisture, pressure and particle size on the agglomeration of biomass feedstocks using a single compaction unit.
- (b) Interactions between densification type (compacts vs pellets vs raw) and the rate of physical and biological/chemical degradation during storage of poultry litter, switchgrass pine wood and peanut hulls.

APPROACH AND METHODOLOGY

The four biomass feedstocks used in the proposed project are wood residue (woody biomass), switchgrass (energy crop), poultry litter (agricultural waste) and peanut hulls (agricultural processing residue). These biomass feedstocks represent each of the four major sources of biomass feedstocks (Perlack et al., 2005) that are potentially available for conversion into bioenergy and biofuels. The specific methodologies used in relation to the objectives of the project are as follows.

Objective 1: Effect of pressure, moisture and particle size on the agglomeration of biomass feedstocks. Initially, a single cylindrical (1" or 25.4 mm diameter and 135 mm length) compaction unit (Fig. 1) was fabricated. The compaction unit was fabricated such that it can be attached to the crosshead of a high capacity Texture Analyzer (Model HD, Texture Technologies, Scarsdale, NY). Due to the maximum capacity of 500 kg load for the Texture Analyzer, the compaction study could only be carried out with a maximum pressure of 8.4 MPa. Therefore, experiments were designed with the aim of producing cylindrical compacts from the four biomass feedstocks with pressures of up to 8.4 MPa. Unfortunately, initial results showed only poultry litter could be compacted at pressures less than or equal to 8.4 MPa. Stable compacts could not be produced from the remaining three biomass feedstocks irrespective of their moisture contents.



Fig. 1. Example of cylindrical compact produced from poultry litter

This subsequently led to the fabrication of another brick-like compaction unit (2" by 2" [50.8 mm by 50.8 mm] brick shaped die – height of 12" [304.8 mm]) that could be attached to a hydraulic system with a load capacity of 50 tons (Fig. 2). Compaction of the remaining three biomass feedstocks were then carried out at pressures of 8.6 MPa, 10.3 MPa, 17.2 MPa and 22.3 MPa.



Fig. 2. Example of manufactured rectangular compact.

Objective 2: Physical and chemical changes and comparison to pelleted and raw biomass feedstocks. Physical stability test was carried out on the compacts after 2 months of storage. For the cylindrical compacts, the strengths of the compact manufactured from samples conditioned to moisture contents between 31.7% to 41.4% (w.b.) were obtained by means of a 12.7 mm diameter round probe (Model TA-23, Texture Technologies, Scarsdale, NY). The compact was placed on a flat plate in its natural position (i.e. radial dimension was in the same direction as that of the compressive force). The probe (attached to the crosshead of the texture analyzer) was then used to compress the compact at a speed of 1 mm/s. The force required to rupture the compacts was obtained from the maximum force in the force deformation curve.

For the brick compacts, the force that is required for the compacts to deform by 10 mm was used as a measure of physical stability. Cylindrical (puncture type) probe (11 mm diameter and 69 mm in height – Model TA 212, Texture Technologies) was connected to the crosshead of Texture Analyzer and compression was carried out at the rate of 1 mm/s.

The energy (using Model C200 bomb calorimeter, IKA Works Inc., Wilmington, NC) and ash (Sluiter et al., 2008) contents of the compacts were also measured and compared to those of raw and pelleted samples. Pelleting of the biomass feedstocks were carried out according to the procedure published elsewhere (Fasina, 2008; Colley et al., 2006).

FINDINGS

Density and physical stability of compacts

(a) Density of Compacted Poultry Litter

Initially, compaction (pressure range of 5.0 to 8.4 MPa) was carried out on poultry litter samples that were conditioned to moisture contents ranging from 16.5% to 29.0 % (w.b.). Preliminary evaluation showed that:

- The agglomeration of poultry litter was not achieved at applied pressures less than 5.0 MPa,
- Poultry litter has to be compacted to a minimum density of 765.6 kg/m³ (Figure 1), and
- The density of agglomeration after compaction increased with moisture content.

Regression analysis showed that within the moisture content range of 16.5% to 29.0% (w.b.) and the pressure range of 5.0 to 8.4 MPa, the following relationship (Equation 1) can be used to predict the density (kg/m³) of compacts as a function of moisture content (% , w.b.) and pressure (MPa).

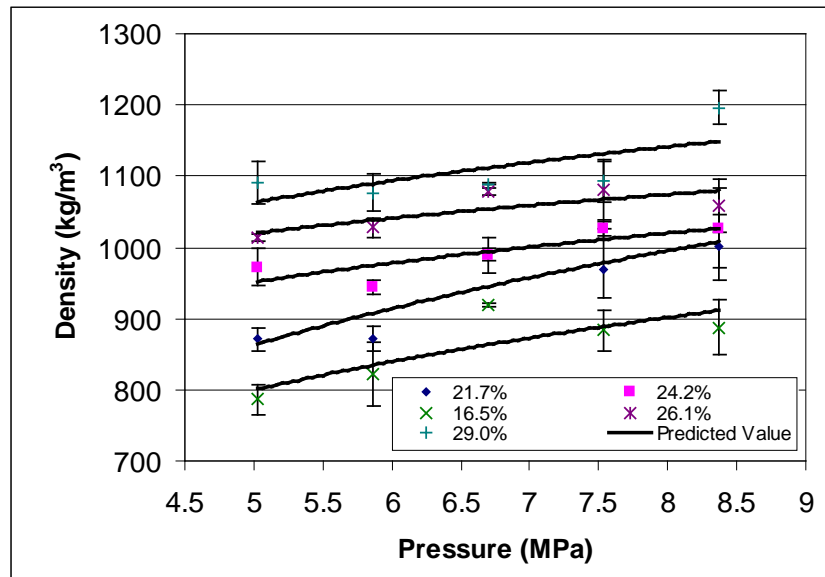


Figure 1 Effect of moisture content and pressure on the density of poultry litter compacts

$$\rho_{compact} = 159.994 + 20.343 * M + 187.075 * \log(\sigma), R^2 = 0.907 \quad (1)$$

Based on the above results, the second set of compaction tests was conducted at higher moisture values (31.7% to 41.4%, w.b.) with the hypothesis that less energy would be required to compact poultry litter at higher moisture contents, since moisture seems to act as a binder during the compaction process. Statistical analysis ($P < 0.05$) showed that the densities from the second set of experiments were not significantly different from those obtained by the first set of experiments. However, the following observations were made from the second set of compaction tests:

- (a) It was possible to produce poultry litter compacts at pressures less than 5 MPa. Successful agglomeration occurred at pressures as low as 0.84 MPa. It should be recalled that compaction was not possible below 5 MPa for samples with moisture contents less than 29.0%.
- (b) At moisture contents greater than 37.6% and pressures greater than 5 MPa, it was extremely difficult to compact poultry litter. This is because the samples began to exhibit fluid like (or slurry) behavior at these higher pressures and therefore could not be contained within the die.
- (c) Within the pressure range of 0.84 to 5.9 MPa the density (kg/m^3) of the compacts increased logarithmically with increases in applied pressure (MPa) and increased linearly with increases in the moisture content (% , w.b.) of the samples (Figure 2 & Equation 2).

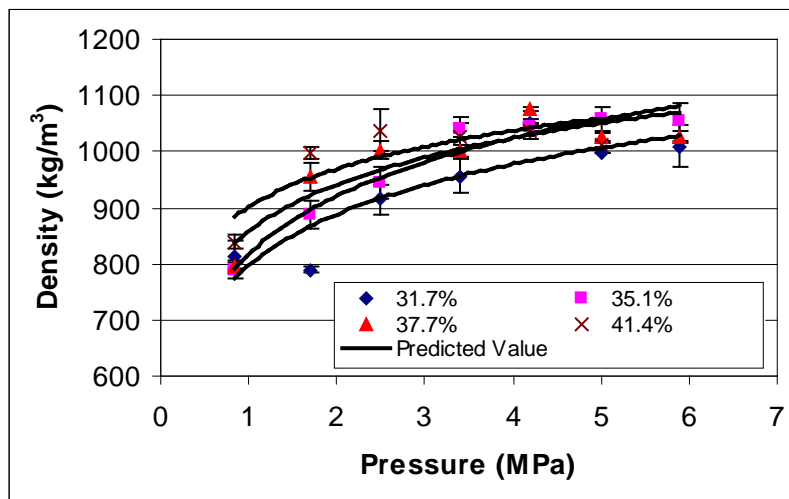


Figure 2 Effect of moisture content and pressure on the density of poultry litter compacts

$$\rho_{compact} = 574.570 + 7.363 * M + 125.778 * \log(\sigma), R^2 = 0.831 \quad (2)$$

As stated in the materials and methods section, breakage force study was carried out only compacts manufactured from samples that were conditioned to moisture contents between 31.7% to 41.4% (w.b.). Figure 3 shows that the average force required to rupture the compacts (after 2 months of storage) vary from 16.6 N to 357.0 N. This rupture force range is similar to that required to rupture pellets (McMullen et al., 2005) despite the fact that pellets are manufactured at significantly higher pressure (> 50 MPa). Despite the fact that the moisture had no significant effect on density of the compacts after 2 months of storage, the force (N) required to rupture the compacts was significantly influenced by moisture content (% w.b.) in a linear fashion and by pressure (MPa) in an logarithmic fashion (Eqn. 4). This again confirms that moisture act as a natural binder during the agglomeration process. Pietsch (2002) attributed the natural binder effect of moisture on the fact that the coating of moisture on particle surfaces improves the natural adhesion of particles to each other.

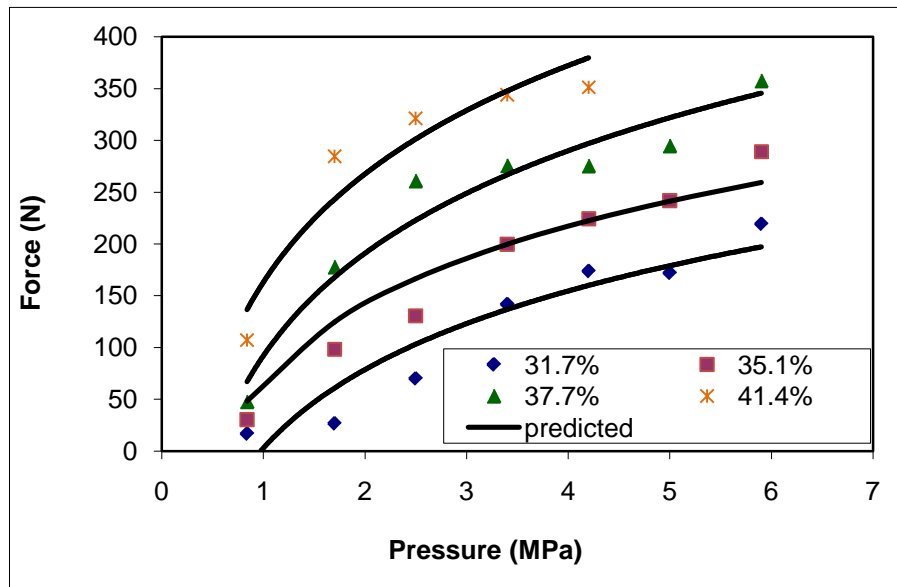


Figure 4. Effect of moisture content and pressure on breakage force of poultry litter compacts after two months of storage.

$$F_{breakage} = 50.917 + 0.462 * M + 108.220 * \ln(\sigma), R^2 = 0.707 \quad (4)$$

$$31.7\% \leq M \leq 41.4\%, \text{ w.b.}; 0.8 \leq \sigma \leq 5.9 \text{ MPa}$$

(b) Compaction of switchgrass, peanut hull pellets and pine wood shavings

The 1” (25.4 mm) diameter compaction unit was also used to carry out preliminary work on switchgrass compaction. The results obtained (Table 1) indicated that the density values obtained were not high enough for the compacts to remain intact during subsequent handling and storage. This was confirmed by visual examination of the compacts. In addition, the effect of moisture content on density was contrary to the results obtained for poultry litter. In the case of switchgrass, increase in moisture content reduced the density of the compacts. We postulate that the addition of moisture to the lignocellulosic materials (such as switchgrass) make them more rubbery in nature. Therefore during the application of pressure, the particles slide against each other rather than compacting especially since the pressures applied were not high enough to overcome this rubbery tendency of the higher moisture content samples.

Table 1: Effect of screen milling size and moisture content on density of compacts at a pressure of 8.3 MPa (using cylindrical die).

Screen size	mc (% w.b.)	Density (kg/m ³)
1/16” (1.59 mm)	15.6	672.9
	18.8	682.3
	24.8	649.93
1/8” (3.18 mm)	15.9	637.9
	19.9	622.5
	25.7	584.4
3/8” (9.53 mm)	15.0	621.2
	21.5	616.2
	28.1	521.6
	31.3	544.3

The results of effect of moisture content on switchgrass compaction as given in Table 1 were confirmed by the density values obtained when switchgrass was compacted at higher pressures (using the rectangular die) and at lower moisture values. Again, similar result on reduced density with increase in moisture content was obtained (Table 2).

Table 2. Effect of moisture content and pressure on density (kg/m^3) and stability of switchgrass compacts (using rectangular die). Sample was milled through 3/8" screen before compaction.

Pressure (MPa)	8.4%		10.5%		17.2%	
	Density (kg/m^3)	Stability (N)	Density (kg/m^3)	Stability (N)	Density (kg/m^3)	Stability (N)
8.6	732.9	630.3	721.0	625.1	687.0	456.3
10.3	784.8	1314.7	744.9	859.7	690.4	631.2

Since highest density was obtained from 8.4% moisture switchgrass samples, subsequent pressure effect was carried out on this sample. Figure 5 shows that a density of 900 kg/m^3 was obtained at pressure of 22.4 MPa. It must be mentioned that this pressure is significantly less than the pressure that is required for pelleting ($>70 \text{ MPa}$). Our visual assessment indicate that the resulting compact remain intact during subsequent handling and storage.

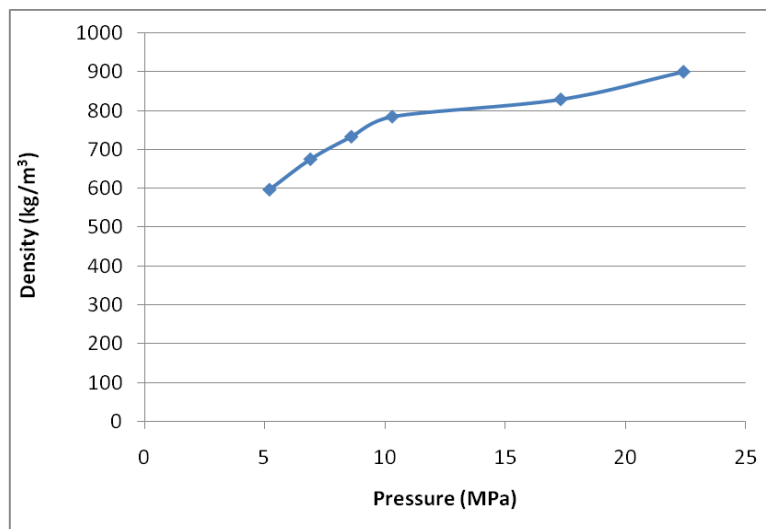


Figure 5. Effect of pressure on density of bricks manufactured from switchgrass milled through 1/8" (3.2 mm) screen. Sample moisture content was 8.42% (w.b.).

Unfortunately, the pressure of 22.4 MPa could not be used in our subsequent tests because of buckling of the die. Tests on pine wood shavings and peanut hulls were therefore carried out at maximum pressures of 17.3 MPa. The results obtained are found in Table 3. Our analysis indicate that the 17.3 MPa pressure is enough to achieve densities that will make the compacts of pine wood shavings and switchgrass stay intact during storage and handling (see stability results

in Table 3). The 17.3 MPa pressure is however not enough for producing stable peanut hulls compacts.

Table 3: Effect of pressure on density and stability of lignocellulosic materials.

Sample	Screen size (mm)	mc (% w.b.)	8.6 MPa	10.3 MPa		17.3 MPa	
			Density (kg/m ³)	Density (kg/m ³)	Stability (N)	Density (kg/m ³)	Stability (N)
Pine wood shaving	3.2	8.94	620.5	700.4	700.4	720.4	900.2
Peanut hull	3.2	8.61	622.0	649.8	304.6	650.2	450.3
Switchgrass	9.5	8.42	732.9	784.8	1314.7	829.2	2025.3

These are the screen sizes used in the hammer mill for preparing the samples for compaction.

(c) Energy and ash contents of biomass feedstocks

Table 4 shows that compaction did not significantly ($P < 0.05$) affect the energy and ash contents of raw, compacted and pelleted poultry litter, switchgrass, peanut hull and pine wood. As expected the ash contents of poultry litter were significantly higher than the ash contents of the other feedstocks. Conversely, the energy contents of poultry litter were significantly lower than the values measured for the remaining three feedstocks.

CONCLUSIONS

Based on the results obtained from this study, it can be concluded that

- (a) Moisture content significantly promotes the compaction of poultry litter. Poultry litter can be compacted into a stable form at moisture content 37.7% and compaction pressure of 5.0 MPa.
- (b) Switchgrass and pine wood behave similarly in their response to pressure. Stable compacts can be formed at pressure of 17.3 MPa for these two feedstocks. Their moisture contents were about 8%. Pressures that are significantly higher than 17.3 MPa may be required for peanut hulls.
- (c) Compaction did not affect the energy and ash contents of the four biomass feedstocks.

Table 4. Energy and ash contents of raw, compacted and pelleted poultry litter, switchgrass, peanut hull and pine wood.

Sample	Type	Energy (MJ/kg)	Ash (% d.b.)
Poultry litter	raw	13.57	34.21
	compact	13.24	35.14
	pelleted	13.33	34.45
Switchgrass	raw	18.55	4.02
	compact	18.93	4.28
	pelleted	18.67	3.96
Peanut hull	raw	19.85	2.52
	compact	19.24	2.66
	pelleted	19.98	2.79
Pine wood	raw	19.85	1.72
	compact	19.43	1.49
	pelleted	20.05	1.34

LIST OF REFERENCES

- Adapa, P.K., Schoenau, G.J., Tabil, L.G., Sokhansanj, S., Crerar, B.J., 2003. Pelleting of fractionated alfalfa products. ASABE Paper No. 036069. ASABE, St. Joseph, MI.
- Colley, Z., Fasina, O.O., Bransby, D. and Lee Y.Y. 2006. Moisture effect on the physical characteristics of switchgrass pellets. *Trans. ASABE* 49(6): 1845-1851.
- Colley, Z., Fasina, O.O., Bransby, D., Wood, C.W., Feng, Y. 2005. Compaction behavior of poultry litter and switchgrass. Paper No: 05-6053. ASAE International Meeting, Tampa, FL. July 17th to 20th.
- Fasina, O.O. 2008. Physical properties of peanut hull pellets. *Bioresource Technology*. 99: 1259-1266.
- Fasina, O.O. and Sokhansanj, S. 1996. Storage and handling characteristics of alfalfa pellets. *Powder Handling and Processing* 8: 361-365.
- Fasina, O.O., Fulton, J.P, Wood, C.W., Owsley, F. and Srivastava, P. 2006. Volume reduction technologies for transporting poultry litter. Paper No. 06-6173. ASABE International Meeting, Portland, OR. July 9th to 12th.
- Mani, S., Tabil, L.G., Sokhansanj, S., 2006. Effects of compressive force, particle size and moisture content on mechanical properties of biomass pellets from grasses. *Biomass and Bioenergy* 30, 648-654.
- McMullen, J., Fasina, O.O., Wood, C.W. and Feng, Y. 2005. Storage and handling properties of pellets from poultry litter. *Applied Engineering in Agriculture*. 21(4): 645-651.
- Nandi, S., Maurer, J., Hofacre, C., Summers, A.O. 2004. Gram-positive bacteria are a major reservoir of Class 1 antibiotic resistance integrons in poultry litter. *Proceedings of National Academy of Sciences* 101(18): 7118-7122.
- Perlack, R.D., Wright, L.L., Turhollow, A.F., Graham, R.L., Stokes, B.J., Erbach, D.C., 2005. Biomass as feedstock for a bioenergy and bioproducts industry: the technical feasibility of a billion-ton annual supply (www.osti.gov/bridge). United States Department of Energy. 60 pp.
- Pietsch, W. 2002. Agglomeration Processes: Phenomena, Technologies, Equipment. Wiley-VCH. 614pp.
- Sluiter, A., Hames, B., Ruiz, R., Scarlata, C., Sluiter, J. and Templeton, D. 2008. Determination of ash in biomass. Technical Report NREL/TP-510-42622.
- Sokhansanj, S. and Turhollow, A.F. 2004. Biomass densification – cubing operations and costs for corn stover. *Applied Engineering in Agriculture*, 20: 495-499.
- Tabil, L. G., Sokhansanj, S., 1996. Process conditions affecting the physical quality of alfalfa pellets, *Applied Engng. Agric.* 12, 345-350.
- Wood, B.H., Wood, C.W., Yoo, K.H., Yoon, K.S. and Delaney, D.P. 1999. Seasonal surface runoff losses of nutrients and metals from soils fertilized with broiler litter and commercial fertilizer. *J. Environ. Qual.* 28: 1210-1218.

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Publications and Presentations

Bernhart, M., Fasina, O.O., Fulton, J. and Wood, C.W. Compaction of poultry litter. Manuscript sent to Bioresource Technology. Awaiting comments from reviewers.