

**FINAL REPORT**  
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**Extrusion and Molding of Animal Co-Product Based MBM Biopolymers**

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**Lay Summary:**

This research was focused on the use of meat and bone meal (MBM) in the production of bioplastics for potential horticultural and geo-structural applications. The processing was conducted using low-cost, scalable manufacturing techniques such as melt compounding, extrusion, calendaring, and thermoforming. The as-received MBM was milled and sieved to reduce particle size. Based on literature studies and previous studies in our lab, glycerol was utilized as a processing aid (plasticizer) at 30 wt%. However, glycerol plasticized sheets did not possess adequate mechanical strength, only a hundredth that of synthetic plastics like polyethylene. They also suffered from quick aging as the plasticizer is lost over time. Therefore, chemical modification of MBM with calcium hydroxide (CH) and maleic anhydride (MAH), and physical blending with polyethylene was conducted. CH content of up to 10 wt% increased the tensile strength (TS) of the sheets to 4 MPa and the modulus to 340 MPa, which is similar to that of LLDPE. However the sheets were still susceptible to moisture. This allowed its utilization in the form of sheets as seed-growth mats that ultimately degrade in soil, i.e., excavation is not required. To further enhance water-resistance and shape integrity, MBM was blended with synthetic polymers like LLDPE (at 30 wt%). The perforated MBM-PE blend sheets were combined with calcium hydroxide modified sheets to form composites with good structural properties while also maintaining water absorption to allow germination of seeds. Finally, MBM was modified and cross-linked with MAH to lower the moisture uptake while maintaining complete biodegradability (unlike polyethylene blend). The MAH-modified MBM sheets were successfully processed into seed growth planters using thermoforming, a low-cost industrial manufacturing process. The germination of seeds was verified as was its structural integrity over a limited duration. An invention disclosure has been filed with the University based on this composition and end-use.

**Objectives:**

The primary objectives of this project were to:

- (i) Convert meat-bone-meal (MBM) into biodegradable plastic-like products; and
- (ii) Develop environmentally friendly and industrially scalable processes for the purpose.

The potential applications of such biodegradable materials include seed growth planters and geo-structural sheets for industrial horticultural applications. The specific research objectives have been compounding, extrusion and roll-mill calendaring of the MBM-derived materials into sheets by “melt” processing, and characterization of microstructure, permeability, and mechanical properties of the resulting films/sheets

## **Project Overview:**

### Introduction:

Because of environmental sustainability concerns and increasing prices of petroleum, there has been increased interest in the development of plastic-like materials (commonly called “bioplastics”) derived from agricultural products. The agricultural products include soy protein, corn starch, cellulose esters [Zhang et al., 2007] (Ogale et al., 2000)] and co-products like lignin, soybean meal, feather meal, blood meal meat and bone meal and others [(Glasser and Leitheiser, 1984), (Pickering, 2010; Sharma et al., 2008)]. Meat and bone meal (MBM), which is an animal co-product from the rendering industry was investigated in this study. The material has become attractive as biomass source to produce bioplastics, mainly because of the restrictions of its use as an animal feed ingredient due to association with bovine spongiform encephalopathy disease, at least in certain geographic locations (e.g., Europe). The annual production of meat and bone meal is estimated at 5 billion pounds. It has a protein content of greater than 50% and has the potential to be utilized in bioplastics, similar to other protein materials like soy, blood meal, keratin which have seen significant research [(Jane, 1996; Martelli et al., 2006; Pickering, 2010)]. Therefore, the goal was to develop bioplastic products from meat and bone meal protein for horticultural and geo-structural applications using industrially scalable processing routes.

### Materials and Methods:

#### *MBM*

Meat and bone meal (MBM) protein (Darling International, Inc.) was used throughout this study. It is an animal co-product with an approximate composition of 50% protein, 8-12% fat, 4-7% moisture, and 35% ash. Because as-received MBM contains large bone particles, it was milled before further processing. The milled MBM sample was sieved through two sieve plates to obtain (i) a coarse grade that was the bottom product of sieving through a 16 mesh sieve (1 mm opening) for a  $97 \pm 2\%$  yield, and (ii) a fine grade that was the bottom product of sieving grade (i) further through a 60 mesh (250  $\mu\text{m}$  opening) that resulted in a yield of  $65 \pm 2\%$ . Preliminary studies were conducted on the coarse grade because of the higher yield, but most of later studies focused on the fine grade because of superior properties.

#### *Glycerol and Calcium hydroxide modification*

Glycerol (SIGMA- Aldrich) was added to the MBM as plasticizer at 15%, 30% and 45 wt% compositions. Following the determination of plasticizer content, the next step was the calcium hydroxide (CH) modification of MBM at 0%, 3%, 7% and 10 wt%. Calcium

hydroxide (VWR International) was initially dissolved in glycerol to form a viscous white paste that was then manually mixed with MBM to form a dough. The dough was intensively compounded in a Haake Rheomix 600 batch mixer at temperatures ranging between 80 and 120°C for a mixing time of 15 to 30 minutes forming consolidated rubbery chunks.

#### *Maleic anhydride (MAH) modification*

MAH was reacted with glycerol in 3:1 ratio by weight. The formed ester resin (glycerol resin) was mixed with 50% MBM in the batch compounder at 100°C for 5 mins.

#### *Blending with LLDPE*

Coarse MBM was mixed with 5%, 10%, 20%, wt% linear low density polyethylene (Dowlex 2045 LLDPE, MFI=1.0 g/min) in a Haake Rheomix 600 batch mixer at 100°C for 15 mins at 60 rpm.

#### *Thermal compaction*

The rubbery chunks (about 13 g) of MBM with modifiers were thermally compacted in an open mold 100 mm x 100 mm using a press (Carver Model 389.4PR1B00) at 6 MPa and 140°C. A holding time of 2 min was allowed for heat transfer to the mold and subsequent softening of the blend. The final load was applied for 2 min and the sample was subsequently cooled to nominal ambient conditions (40°C) under pressure before removing the sheet from the press.

#### *Calendering*

The blends of MBM with different fractions of LLDPE were calendered into sheets using Collin calender mill through a 500µm gap at 135°C and speed of 5 to 15rpm.

#### *Thermoforming*

MAH-modified MBM sheets were successfully thermoformed into three-dimensional shapes using an aluminum tool and a lab-scale unit, EZFORM SV 1217-110V tablet vacuum forming machine. Such objects served the purpose of simulating seed growth planters.

#### *Chemical and Microstructure*

Optical microscopy (Olympus BX60) and scanning electron microscopy (SEM – Hitachi S4800) were used to analyze the texture and surface characteristics of the sheets. Fourier-transform infrared (FT-IR) analysis was conducted using a Nexus 870 FT-IR ESP, Nicolet

and OMNIC version 5.1 analysis software. The spectra of all the sheets, MBM powder, and glycerol were obtained using a Germanium ATR (attenuated total reflectance) accessory over a spectra range of 4000 - 600  $\text{cm}^{-1}$ . For each composition, spectra were obtained at three different points of the sheet and 32 scans with 8  $\text{cm}^{-1}$  resolution were averaged.

### *Tensile Properties*

Tensile tests were conducted following the ASTM D638-10 procedure except that rectangular strips were used rather than dog-bone specimens. The samples were nominally 0.6 mm thick, 1.3 cm wide and 11.4 cm long, and the gauge length was set at 5.7 cm. Mean thickness of the samples was obtained from five points with a Nikon Dig-micro, MF-5-01. Mechanical testing of the sheets was performed at a cross-head speed of 0.25 cm/min (Applied Test Systems Inc., Series 900). A minimum of five replicates for each composition were tested to calculate average values. Samples were conditioned for 24 hours at RH levels of 20%, and 50%. Conditioning was also done in a vacuum oven at 50°C (~75 cm Hg vacuum) for 24 hours to obtain almost dry sheets.

### *Water Vapor Permeability*

The tests were carried out following the ASTM E 96-05 [Standard Test Methods for Water Vapor Transmission of Materials]. Two replicate circular discs were cut each having an area of 28.3  $\text{cm}^2$ . These were placed on the testing cups each containing 15 ml of distilled water; cups were tightened by screws leaving an exposed area of 19.6  $\text{cm}^2$ . The cups were placed in the WVP testing chamber (Model 506A Electro-tech Systems Inc.) maintained at controlled relative humidity (RH) and temperature. Within the chamber, a Denver instrument Model # P-603-D balance was used to obtain mass as a function of time. The temperature and humidity were stabilized for 24 hours before testing began. Measurements were taken at 1 hour intervals for the first 12 hours, and then every 5 hours. From a linear regression of the curve, water vapor transmission (WVT) was calculated as:

Water vapor transmission (WVT) in  $\text{g}/\text{m}^2/\text{s} = (\text{slope}/\text{Area}) \times 1\text{hr}/3600\text{s}$

Then, water vapor permeability (WVP) was calculated as:  $\text{WVP in g}/\text{m}\cdot\text{s}\cdot\text{Pa} = ((\text{WVT}) \times T)/\text{SVP} (\text{RH}_1 - \text{RH}_2)$ ; where SVP = saturation vapor pressure at test temperature, T = average thickness of the test specimen, and

$\text{RH}_1$  and  $\text{RH}_2$  = relative humidity in the test cup at 100% and chamber at 50%, respectively.

## **Results and Discussion:**

The batch compounding of MBM with different plasticizer content (15, 30% and 45 wt%) at 100°C, 60rpm for 15mins produced variable material as shown in figure 1a below. MBM with 15wt% did not produce a consolidated mass, while that with 30wt% and 45wt% produced consolidated chunks. It was observed, that the different material when subsequently thermal compacted with the press (figure 1b), only the consolidated chunks formed plastic sheets. Therefore, it was concluded that, glycerol content greater than 15wt% was required for plasticization of MBM plastics.



Figure 1a. Evolution of texture of compounded MBM with different plasticizer contents.



Figure 1b. Illustration of the formation of a bioplastic sheets from plasticized and batch compounded meat and bone meal.

### Optimization of glycerol content

Since 15 wt% glycerol content was ruled as insufficient in the processing of MBM bioplastic sheets, further analysis looked at sheets produced with 30 wt% and 45 wt% plasticizer content. Dynamic mechanical analysis was used to establish the optimum glycerol content by assessing the dynamic moduli as a function of temperature from sub-ambient to about 80°C. Figure 2 shows a dynamic temperature ramp of MBM sheets plasticized with 30 wt% and 45 wt% glycerol in tensile mode at 0.05% strain and 1 Hz frequency. Clearly, the moduli of sheets with 30 wt% are greater than that of sheets with 45 wt% glycerol content. Therefore, 30 wt% glycerol content was taken as the optimum plasticizer content sufficient in the thermal processing of MBM bioplastic sheets.

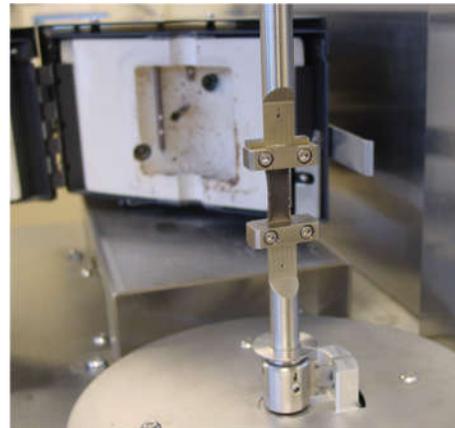
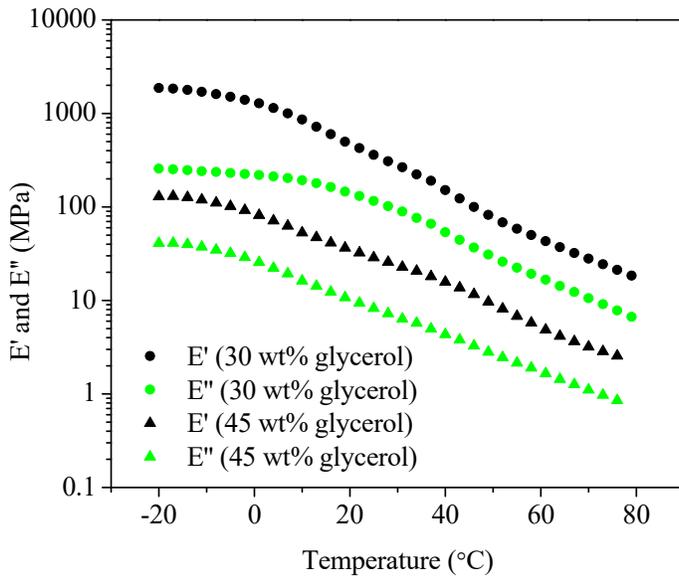


Figure 2. Dynamic mechanical analysis of MBM sheets with 30 wt% and 45 wt% plasticizer content. The plot shows the dynamic temperature ramp at 0.05% strain and 1 HZ frequency. The photograph illustrates the setup of the sample in the tensile fixture of the test unit.

## Calcium Hydroxide Modification

As the concentration of the calcium hydroxide increased from 0% to 10 wt%, the solidified material became stiffer. The color of the films remained light brown, as displayed in figure 3 below. It is evident from the photographs that the unmodified sheets were very soft and pliable, whereas the 10 wt% calcium hydroxide sheets were rigid.

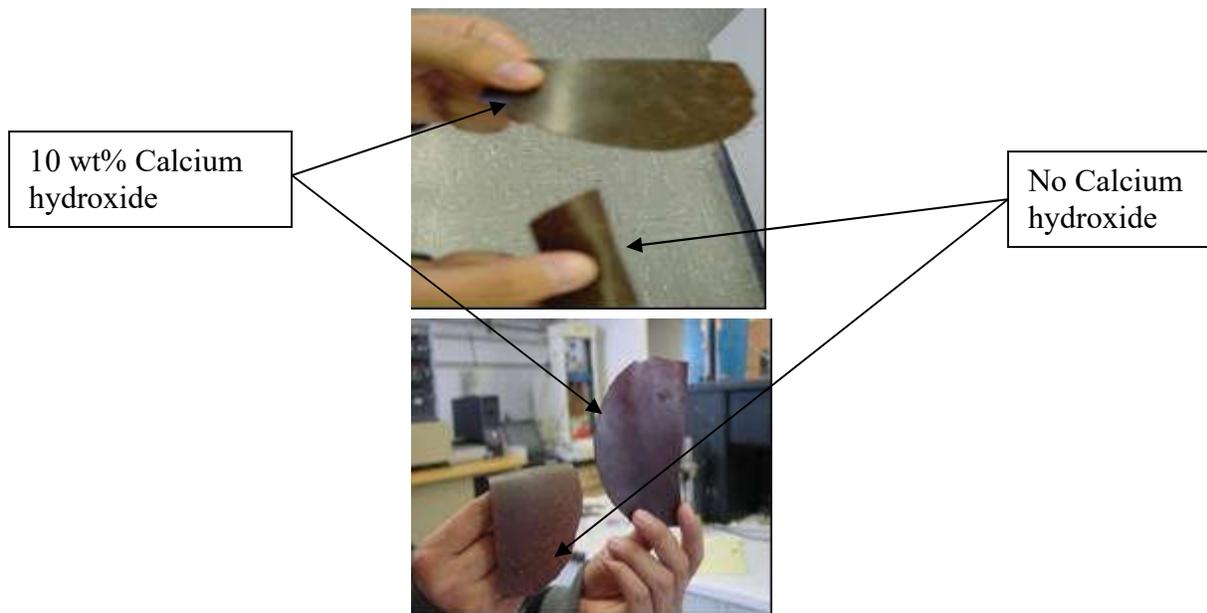


Figure 3. Characteristics of soft 0% and hard 10% calcium hydroxide modified sheets

## Mechanical properties of calcium hydroxide modified sheets

Table 1 below displays the tensile modulus, strength and strain to failure as a function of calcium hydroxide (CH) concentration of the plasticized sheets obtained from the fine grade of milled MBM. As the CH concentration increased, the tensile strength initially decreased for 3 wt% CH modification to half the value for non-modified sheets ( $0.8 \pm 0.1$  MPa). However, for higher CH content, TS increased by a factor of about four, to  $3.22 \pm 0.38$  MPa for 7 wt% CH. Increase of CH to 10% resulted in sheets with TS  $\sim 5$  times that of sheets with 0 wt% CH. Strain to failure generally decreased as the CH content was increased from 0% to 10 wt%. Sheets with 3 and 7 wt% CH, had their strain to failure decrease by about 40% while that of 10 wt% CH sheets, decreased by 75% compared to unmodified sheets. Similar to the tensile strength, tensile modulus (TM) of the sheets first decreased when 3 wt% CH was added, but increased by a factor of 3 and, 8 when 7% and 10 wt% CH were, added respectively. The tensile results reported in the table confirm the physical observations made above. The increased TM and TS is attributed to the crosslinking of MBM proteins via calcium ion interactions based on the FTIR analysis of the CH modified sheets in Figure 4.

Table 1. Comparison of tensile strength (TS), strain to failure, and apparent tensile modulus (TM) of sheets made from fine MBM with different CH contents. Test samples were pre-conditioned in a 75 cm Hg vacuum at 50°C for 24 hrs (n = 5)

<b>Composition</b>	<b>TS (MPa)</b>	<b>Strain to failure (%)</b>	<b>Modulus (MPa)</b>
<b>0% CH</b>	0.84 ± 0.10	8.90 ± 1.20	40.16 ± 2.90
<b>3% CH</b>	0.48 ± 0.06	4.95 ± 0.50	34.84 ± 2.23
<b>7% CH</b>	3.22 ± 0.38	6.52 ± 2.45	139.4 ± 20.10
<b>10% CH</b>	3.96 ± 0.55	2.10 ± 0.39	341 ± 50.78

In Figure 4, FTIR spectra for sheets containing different CH composition (0%, 3%, 7% and 10 wt%) are displayed. A comparison of peaks between 1750 and 1100  $\text{cm}^{-1}$ , shows that at 3 wt% lime modification, no significant change in chemical structure is observed. Significant chemical changes are observed at CH concentration of 7 wt% or higher. Because there is increased interaction between the protein chains, broadening is observed in the amide II through amide III region. It can therefore be inferred that addition of CH content greater than 7 wt% increases protein chain interaction

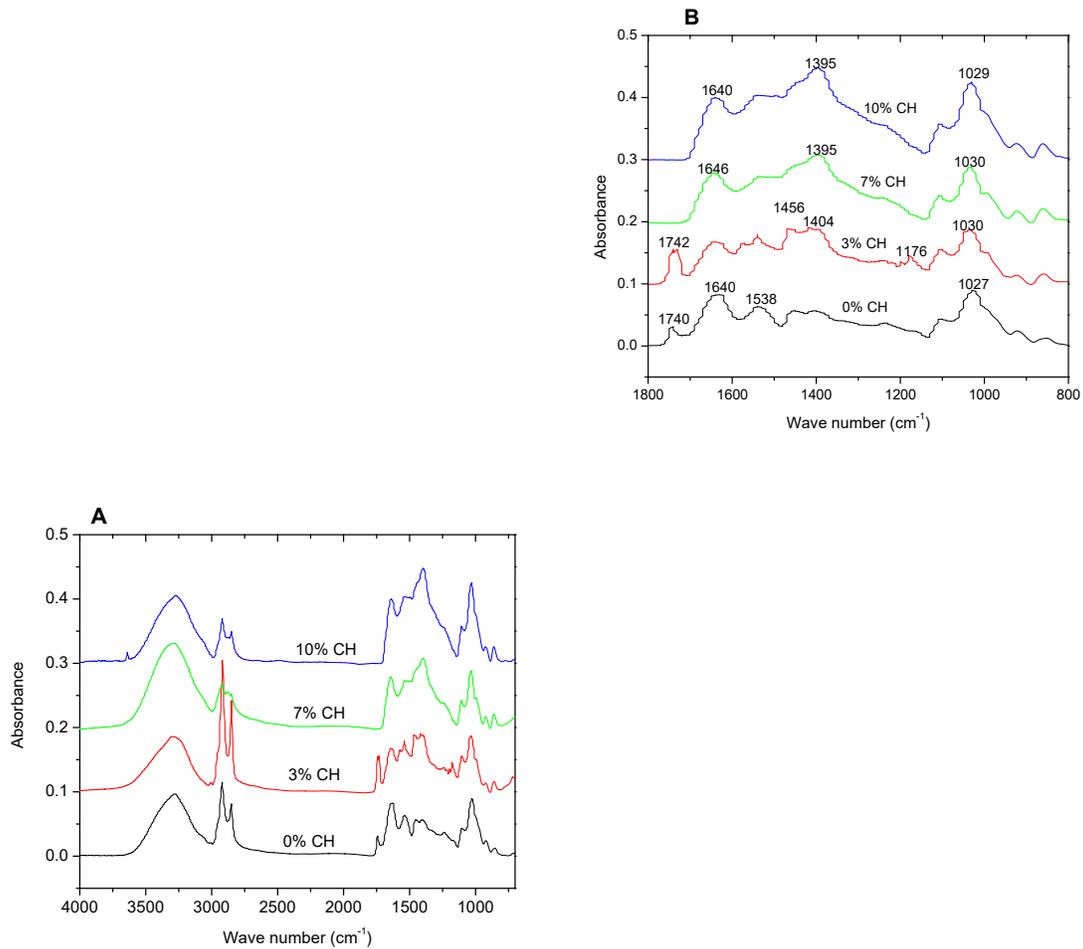


Figure 4. FTIR spectra comparing the molecular structure of MBM plastic sheets modified with different calcium hydroxide composition: (a) spectra over a wider range of wave numbers, and (b) zoomed-in spectra of fat and protein characteristic bands

### Effect of Environmental Humidity

Figure 5 presents stress-strain plots for 7 wt% CH modified MBM sheet showing the effect of environment humidity on the mechanical properties. The samples were preconditioned at 0%, 20% and 50% percent relative humidity (RH). At 0% RH, the samples showed glassy behavior with a high modulus of 140 MPa and low strain to break of about 10%. When the RH was increased to 20%, the sheets demonstrated a rubbery behavior with the modulus decreasing by almost an order of magnitude to 17 MPa while the elongation to

break increased by a factor of 3 to 30%. Increase in the relative humidity to 50% decreased the modulus further to 13 MPa and also decreased the strain to failure to values close to those of samples conditioned at ~ 0% RH.

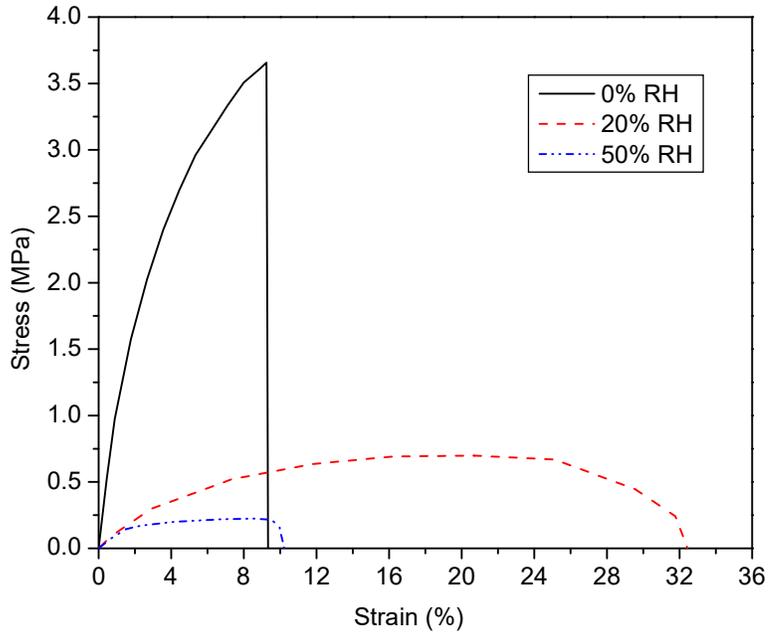


Figure 5. Stress-strain plot showing the effect of environment humidity on the tensile properties of 7 wt% CH modified sheets from fine MBM at 25°C. Test sample were pre-conditioned for 24 hrs at each humidity level

## Seed grow experiments with CH-Modified MBM sheets

Since calcium hydroxide-modified modified sheets are moisture sensitive, they easily absorb water, and are suitable for use as seed mats. Figure 6a shows an experimental set up where seeds in one batch were put in bare soil over which the MBM sheet was placed as a mulch (blue) and the second batch, the grass seeds were sandwiched in two MBM sheets at room temperature with a cover press at about 250 lbf.



Figure 6a: MBM sheets/grass seed experiment. (Yellow- MBM/grass sandwich where each of the sandwich sheets was 0.6mm thick; Blue-MBM sheet mulch which was 0.6mm thick)

Figure 6b is a picture showing that in either batch, the grass germinated and penetrated the MBM sheet. Seedlings in bare soil were 3.5" – 4" tall while seedlings in MBM sheet were 0.5" – 2" tall and others were in late germination stage. Therefore, despite the mechanical degeneration of the CH modified MBM sheets, they are utilizable as seed growth mats. This cannot be achieved with synthetic polymers.



Figure 6b: After 11 days, grass in both pots had germinated though to different heights especially in the MBM sandwich

## Blends of MBM with LLDPE

MBM compounded with LLDPE was calendered at 135C and rpm varying from 5 to 15. A continuous sheet about 6 inch wide, 0.5 mm thick and 40 inch long was formed as shown in Figure 7 photographs.



Figure 7. Calendering of MBM-LLDPE blend sheets using the Collin W 100T Calendering unit

## Mechanical properties of MBM-LLDPE blends

Table 2 summarizes the tensile properties of sheets calendered from the blend of MBM with different fractions of polyethylene. The TS of the composite sheets increased linearly from 0.74 MPa to 6.27 MPa as the LLDPE content was increased from 10 to 60 wt%. Similar to the TS, strain-to-failure increased with increasing wt% of LLDPE though it did not increase proportionally. However, even at 60 wt% LLDPE the TS and STF of the composite sheet is ~20% and 15% that of LLDPE respectively. For the modulus, samples with 15%, 20% and 30wt% LLDPE had higher TM than LLDPE, however the modulus of samples with higher PE content (40 wt% and 60 wt%) was not statistically different from that of LLDPE. The sheets with 10 wt% LLDPE had about half the modulus of LLDPE.

The increase in the TS and STF of the composite sheets is due to the encapsulation of MBM particles during melt mixing with the batch compounder that enables the PE chain network to develop. The more the PE content, the better the wetting and growth of the chain network as observed in Figure 8 showing the microstructure of the fractured surface of MBM-LLDPE composite sheets.

Table 2. Comparison of tensile strength (TS), strain to failure (STF), and apparent tensile modulus (TM) of MBM-PE blend sheets with different wt% of LLDPE. Test samples were pre-conditioned in 50% RH at 25°C for 24 hrs (n = 5)

Wt% LLDPE	TS (MPa)	STF (%)	Modulus (MPa)
10	0.74 ± 0.10	2.27 ± 0.31	138.83 ± 1.07
15	1.38 ± 0.10	7.09 ± 0.91	398.03 ± 80.15
20	1.98 ± 0.03	7.19 ± 2.61	475.81 ± 47.13
30	2.82 ± 0.26	18.09 ± 1.56	487.08 ± 126.62
40	3.99 ± 0.13	45.44 ± 6.67	450.61 ± 95.15
60	6.27 ± 0.21	107.9 ± 58.93	394.34 ± 40.34
100	31.60 ± 1.05	726 ± 32.17	281.54 ± 44.60

## Microstructure

Figure 8 displays the scanning electron (SEM) micrographs of the fracture cross-section surface of MBM-LLDPE composite with different weight fraction of LLDPE. Generally, it was observed that the MBM domains (dark regions) highlighted red reduced in size and the polyethylene network (light regions) increased with increased PE weight fraction. The increase on the PE network contributes to the observed increase in the TS and STF while the MBM agglomerates are responsible for increase in modulus of the MBM-LLDPE composites. The reduction of MBM agglomerate size is due to improved shear stress transfer with higher melt fractions of PE.

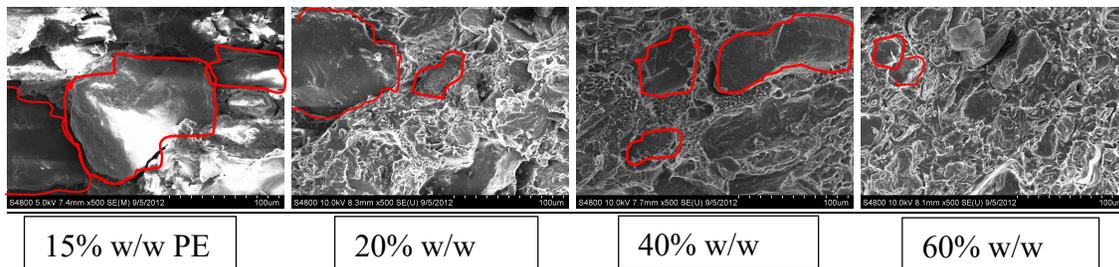


Figure 8. Scanning Electron micrographs showing the fracture cross-section of MBM-LLDPE composite sheets with varying LLDPE content.

## Water vapor permeability

Figure 9 shows a plot of water vapor permeability (WVP) of MBM-LLDPE composites with increasing volume fraction of MBM in the composite. The WVP of the composite sheets followed a power law decrease with increasing fraction of LLDPE.

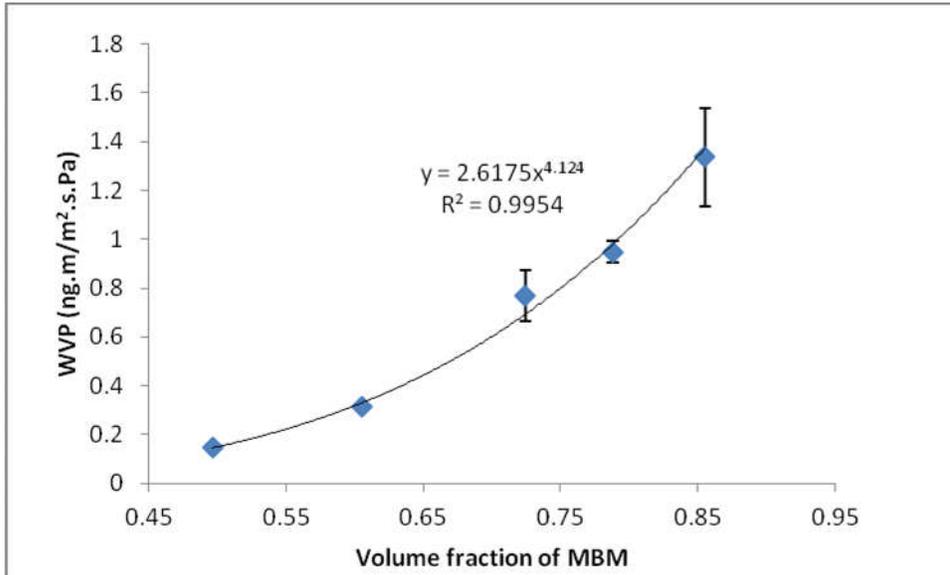


Figure 9. Plot of water vapor permeability of MBM-LLDPE composites sheets as a function of the volume fraction of MBM in the composite.

### **Seed growth in multi-layer MBM-CH and MBM-LLDPE composite sheets**

As discussed earlier, it was observed that MBM sheets allow germination of implanted seeds when placed in a conducive plant growth environment, as confirmed from actual seed growth experiments illustrated in Fig. 10. However, they quickly soak water and lose mechanical integrity, which is important if they are to prevent eroding away of the growing seedlings. Therefore multilayered sheets that can support growth and also maintain some mechanical integrity during seed growth were investigated. Such an approach would be useful for sustainable farming of vegetables and herbs.

In one such experiment, the MBM-grass-MBM sheet was sandwiched in a PE-MBM (15%-85%) sheet with perforations as showed below. The sides of the PE-MBM cover sheet were heat sealed at 140°C and compacted. Grass seeds were used in the study for convenience; vegetable and plant seeds would be used in real application.



Figure 10. Multi-layer sheet (PE-MBM-grass-MBM-PE) 4"x3" of the PE sheet is perforated on either side as shown in the photo

As expected, seedlings germinated through the majority of perforated part of PE-MBM sheet. A few regions showed lack of growth, which might be attributed to thermal or mechanical damage of seeds during encapsulation. This application was submitted to the University IP committee in Spring-summer 2012 as an invention disclosure, CURF # 2012073, "Composite Growth/Mulch Sheets Derived from Synthetic and Bioplastics". The Committee did not recommend it for further consideration, but advised that other applications of MBM be pursued for potential commercialization.

#### **Maleic anhydride modified MBM sheets**

CH-modified MBM tend to age relatively fast in addition to being susceptible to moisture. The aging is attributed to loss of the plasticizer over time. Therefore, further chemical modifications were conducted to reduce moisture sensitivity as well as reduce aging by reaction of glycerol with maleic anhydride (MAH). When MAH is reacted with glycerol, it forms an ester resin which still has good plasticization properties as well as increased interaction with protein residues that have hydroxyl groups. This keeps the glycerol in the sheets and thus maintains mechanical properties. The addition of MAH leads to formation of rigid and brittle sheets, similar to high concentrations of calcium hydroxide. Figure 11 is a photograph demonstrating the stiff nature of MBM sheet modified with MAH. The sheet was found to have a flexural modulus of 2 GPa.



Figure 11. Thermally compacted sheet of MBM-Glycerol resin (50-50). The sheet is 3" long, 3" wide and 1.5 mm thick.

## Thermoforming of MAH-modified MBM sheets

The engineered bioplastic made from MBM and glycerol resin is glassy and rigid at room temperature. However, when exposed to temperature higher than 60°C, it becomes malleable and can be ‘thermoformed’ into shaped articles as demonstrated in the figure 12 photographs below.

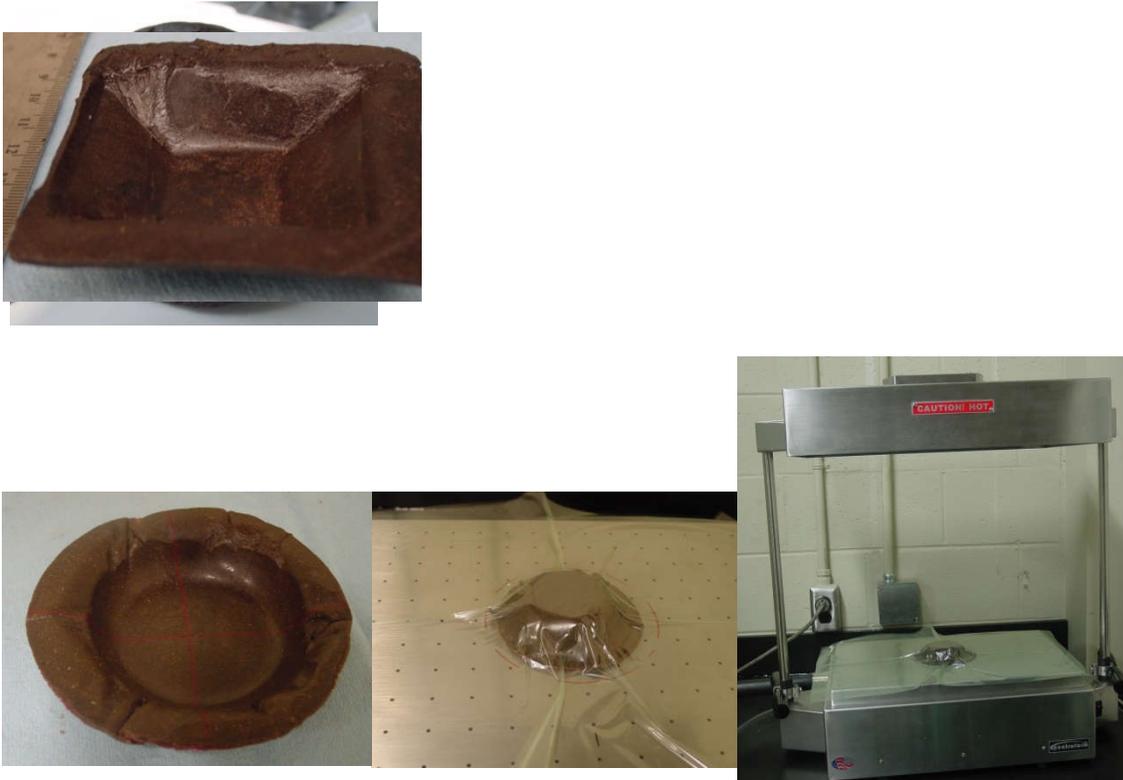


Figure 12. Vacuum thermoforming of MAH modified MBM sheets (50-50 wt%)

The thermoformed containers were investigated for their potential use as a seed growth planter. Soil was placed in the planter and grass seeds added. The assembly was placed on the window sill and watered daily. By day 10 about 5 seeds had germinated, whereas by day 14, a large fraction of seeds had done so (15 seeds or about 50% yield). It is noted that the MBM bioplastic planters remained intact over the entire growth period despite being watered daily.



Figure 13. Investigation of seed growth support of the tray made from MBM-MAH bioplastic

An invention disclosure has been recently filed with the University IP committee entitled “Thermoformed Seed Growth Planters from MBM-Derived Bioplastic”. This was done based on the Committee’s earlier (June 2012) recommendation that other applications of MBM be pursued for potential commercialization.

### **Conclusions:**

The use of glycerol facilitated processing of Meat and bone protein in into bioplastic sheets using conventional plastic processing techniques. It was determined that the glycerol content (plasticizer) required for sheet formation is greater than 15 wt%. 30wt% plasticizer content was established as being optimum based on the performance analysis of the sheets with different plasticizer content using dynamic mechanical analysis.

Investigations in the chemical modification of MBM using calcium hydroxide, revealed that it increased tensile strength and modulus of the sheets by a factor of 4 to 8 while the strain to failure decreased by 40 to 70% of that of the unmodified sheets.

Chemical modification with maleic anhydride (MAH) helped reduce aging of MBM sheets and also increased strength and modulus of the formed sheets with the modulus increasing by more than two orders of magnitude than the unmodified sheets. Even though the MAH modified MBM sheets have such a high modulus, they were still thermo formable at temperatures ranging between 80 to 100°C into shaped articles, that could potentially be utilized as seed growth vessels.

Consolidation of MBM with low fractions of LLDPE (less than 30 wt%) reduced the moisture sensitivity of MBM and stabilized mechanical properties of the composite sheets.

### **Impacts and Significance:**

This research project has successfully established the technical feasibility of chemical modification of MBM, a co-product of the rendering industry, into bioplastics materials suitable as biodegradable seed growth planters and mulch sheets. The processing studies have proven that low-cost, commercial processes such as thermoforming may be used to produce the products.

New commercial applications will necessarily require further development studies because use of synthetic plastics is very well accepted currently. However, as environmental restrictions and petroleum products prices fluctuate, use of MBM-derived materials could easily present a viable alternative in the future.

**Publications:**

S. Lukubira and A. A. Ogale, “Thermal Processing and Properties of Bioplastic Sheets Derived from Meat and Bone Meal”, accepted 20 February 2013, published online DOI#39156, J. Applied Polymer Science

S. Lukubira and A. A., Ogale, “MBM-LLDPE Composite Sheets”, *in preparation*, J. Applied Polymer Science

**Outside funding:**

Use of other bio-based precursors for the development of carbon fibers was successfully funded by the Army Research Lab as a 4-year research project entitled, “Carbon Fibers Derived From Sustainable Precursors”, Army Research Office/ SERDP, A. A. Ogale (PI); A. Greene (Co-PI), total \$ 700,000.

**Future Work:**

As discussed during Fall 2012 ACREC meeting, although current market price of MBM makes it a valuable feed source, there are potential regional preferences for its use as a non-feed material. Further development and refinement of materials- methods described in this research report will position FPRF and its members to handle alternatives uses of MBM either due to future environmental restrictions or due to changing economics that favor non-feed application.

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