Development of Affordable Building Materials Using Agricultural Waste By-Products and Emerging Pith, Soy and Mycelium Biobinders

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ABSTRACT: Along the hot-humid belt, rapidly developing countries that lack affordable building materials have overlooked the potential of agricultural wastes as alternative resources. Globally, 140 billion metric tons of agricultural by-products (ABPs) are generated annually, representing an abundant, renewable material stream. Industrial ecologists have recently investigated the upcycling of ABPs into biocomposites to replace conventional wood products that use harmful urea-formaldehyde, phenolic compounds, and isocyanate resins. This paper evaluates the upcycling of coconut ABP using nontoxic, renewable biobinders under comparatively low-energy conditions to create affordable structural and cladding building materials. In this paper, we investigate the effects of processing variables on board mechanical performance using the ASTM D-1037 standard, these are: (i) fiber processing, (ii) fiber-binder ratios, (iii) pre-pressing methods, by which binders initially adhere to fibers, using established thermal pressing conditions within each biobinders industry. Here, we compare the mechanical properties of medium-high density boards (500-1200 kg/m^3), made from coconut fibers bonded by coconut pith, soy protein, or fungal mycelium, to those of common medium-high density wood and reconstituted wood products.

Keywords: agricultural waste, biobinder, coconut pith, soy protein, fungal mycelium, low embodied energy materials, clean materials, biomaterials

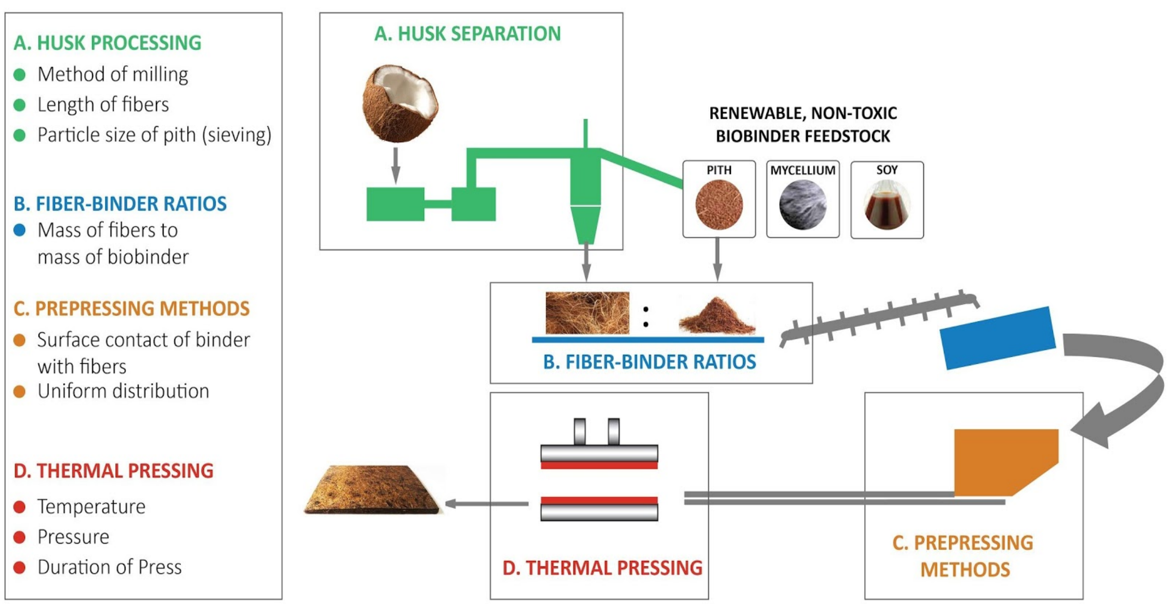


Figure 1: Diagram of Processing Variables for Coconut Fiber - Biobinder Board Production

INTRODUCTION

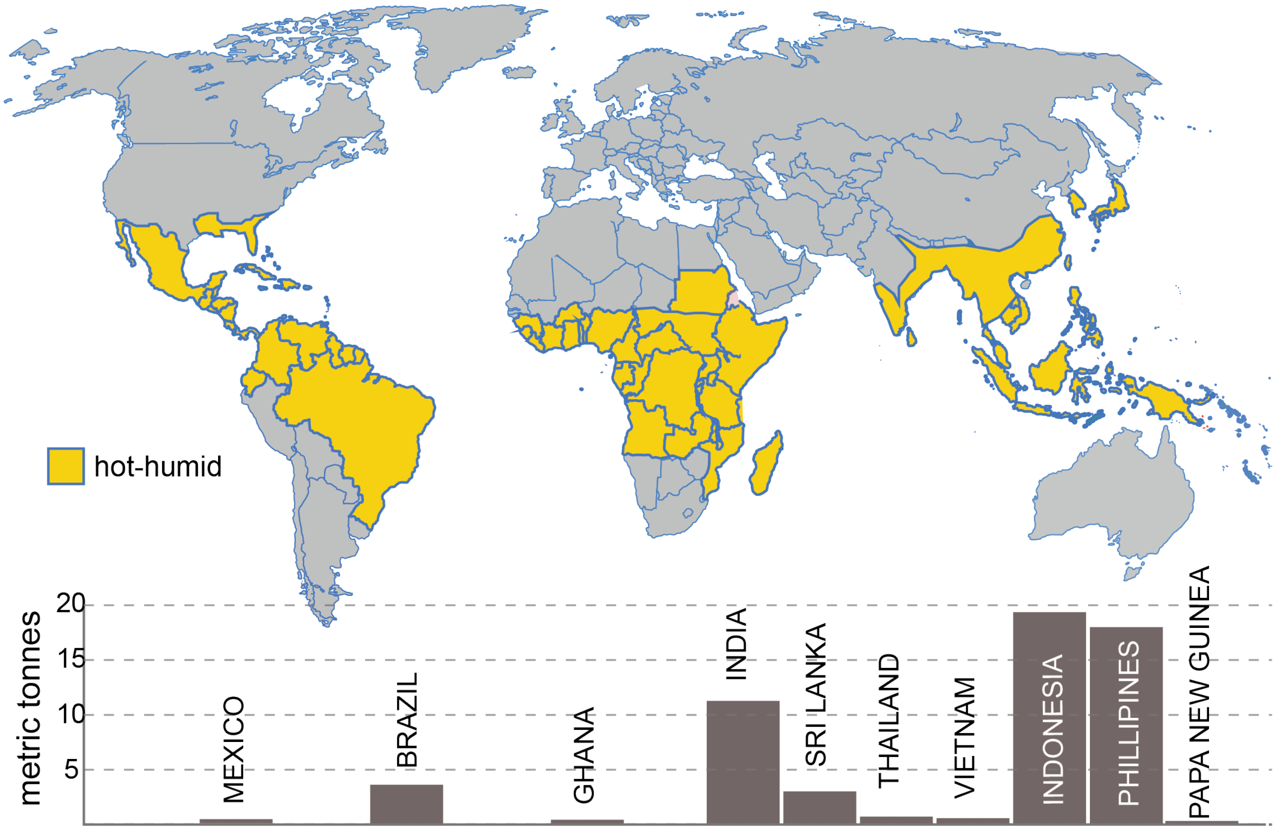


Figure 2: Global hot-humid map showing major coconut producing countries (FAOSTAT 2012 data)

Along the hot-humid belt, where half the world's population is concentrated, rapidly developing countries that lack affordable building materials have not capitalized on the potential of agricultural waste to serve as an alternative building material stream. Grown all-year round in 93 countries on 12.17 million hectares, the coconut palm tree is the most economically cultivated palm by small-scale farmers who make less than $2 dollars a day (FAO 2012). Globally the coconut is largely cultivated for coconut water and dried copra meat derivatives, generating 15-20 million tons of husks annually (van Dam 2003). Coir fibers are natural fibers extracted from the husk surrounding the seed of the coconut. Relative to other agricultural waste, coir fiber's advantage is a result of its high structural lignin content (38-44%) over twice that of other agricultural by-products, high strength-to-mass ratio and low energy conversion properties (van Dam 2004, Müssig 2012). Recent advances in industrial and material science, focused on improving coir extraction methods and optimizing processing conditions, have resulted in coir product applications in the particleboard, fiberboard, insulation and composites industry. While the scope of this paper is limited to the mechanical performance of coconut husk derivatives, this work is part of a larger body of research investigating coconut desiccant building materials as moisture buffering systems.

Since the late 19th century, competing wood and reconstituted wood industries have been dominated by toxic, petroleum-based urea-formaldehyde and other formaldehyde condensed adhesive binders that are responsible for the off gassing of volatile organic chemicals within indoor environments (VOCs) (Brown 1999, Jensen et al 2001). Due to the negative impact of such material emissions on human respiratory health (Krzyzanowski et al. 1990, Garrett et al. 1997), air quality regulations and wood industry standards are rapidly changing to limit the use of such binders.

Coupled with this growing interest to develop renewable non-toxic binders, and progress within the agriculture industry to expand nonfood by-products into growing markets, this paper investigates the performance of agro-based waste material resources derived from renewable protein and lignocellulosic biopolymer resources. The aim of this paper is to evaluate the mechanical strength of coconut fiberboards based on the use of nontoxic, renewable biobinders to form competitive reconstituted board products at low-energy conditions. The biobinders under investigation comprise of (i) pith, found naturally between coconut husk fiber walls comprising 70% of the coconut husk (van Dam 2004) (ii) proprietary soy protein binder from e2e materials and (iii) proprietary fungal mycelium binder from Ecovative Design.

MATERIALS AND METHODS

Extensive research on coconut pith cross-linking behaviour at lower temperatures (~135°C) and pressure (<350psi), relative to the reconstituted wood industry, has been attributed to the dehydration and curing of lignin resulting in thermosetting behaviour during thermal pressing (Varma et al. 1986, van Dam et al. 2004, Greer 2008). Previous research on coconut pith binder has investigated the 100% substitution of synthetic resin for medium density fiberboard production (van Dam et al. 2003, Snijder et al. 2005), pith particleboard production (Greer 2008) and high pressure laminate production towards the reduction of phenolic resin content (Glowacki et al. 2012).

The soy adhesive resin from e2e Materials consists of cross-linking agents and defatted soybean flour, obtained by grinding soy flakes after hexane extraction from soy oil, which react to provide a rigid thermoset binder (Rasmussen et al. 2011, Netravali & Govang 2013, Zhang et al 2014). Ecovative's proprietary binder makes use of mycelium, the vegetative state of fungi in the phylum of Basidiomycetes, to provide structural binding. The fungal vegetative tissue (mycelium) propagates and binds to the coconut coir fibers as it grows into an interconnected fibrous network. The mycelium derives its network strength from chitinous cell walls, imparting high elastic moduli and high flame retardance and low thermal conductivity (Pelletier et al. 2013).

Coconut Husk Fiber Processing

Coconut coir fibers were obtained from Rolanka International, a leading coconut supplier in Atlanta, USA that imports coconut husk derivatives from Sri Lanka. Prior to shipping, coconuts husks obtained from Rolanka undergo 'wet retting', a process where husks are cured in fresh water for three months resulting in dark brown coconut fibers. The highest grade of coconut fibers, bristle coir, composed of longer fibers with higher tensile strength was used for fiberboard production. Two forms of fiber products were investigated, including loose bristle coir fibers and a non-woven coir mat. Both fiber products were stored in a dry environment at room temperature. The length of loose bale fibers ranged from 15-30 cm. Non-woven coir mats were made using needle-punch technology to form a uniformly dense of 1.2 kg/m^3. Long fibers were cut into smaller length of 1-2cm by hand for physical characterization tests. Fiber pore sizes were measured by a FEI 3D Versa Environmental Scanning Electron Microscope. Hammermilling, an industrial process of cutting down coconut bristle fibers using a series of small hammers, employed pneumatic assisted ECO-HMA Colorado Mill Equipment. Resultant fiber lengths were controlled using a milling screen of 0.25" and 0.5" mesh sizes, yielding a range of fibers between 3-20mm and 20-40mm respectively.

Biobinder and Fiber Substrate Preparation
Coconut Pith

Two types of pith were obtained from coconut husk suppliers including compressed pith from Rolanka peat blocks and loose, uncompressed pith particles from Ecofibers Ghana Ltd, a leading coconut supplier in Ghana, West Africa. The raw pith mixture is comprised of a wide range of particles, including parts of the inner coconut shell that were not separated from husk during milling operations. Pith particles were sieved using a stainless steel wire cloth to remove mixture impurities and control particle sizes to 1000μm and 350μm. Pith binder and bristle coir fiber masses were measured using a mass balance according to desired fiber to binder ratios. Pith and fibers were prepressed into sheets before thermal pressing conditions listed in Table 4.

Table 1: Pith binder particle size, fiber substrate characteristics and fiber: pith binder ratios

Board #	Biobinder Size (μm)	Fiber Length (mm)	Binder %
1-3	1000	3-20	50%
4-6	350	3-20	50%
7-9	1000	3-20	50%
10-12	1000	20-40	50%
13-15	1000	3-20	30%
16-18	1000	3-20	50%
19-21	1000	3-20	70%
22-24	1000	3-20	90%

e2e Materials Soy Protein

e2e Materials soy resins are provided in dry and wet resin mixture; the dry powder resin mixes well and adheres to short loose fibers. A known mass of dry soy protein mix and coir fibers are mixed uniformly using a HCM 450 mixer according to fiber-binder ratios (refer to Table 2). Using the wet resin method, the non-woven mats were batch soaked in a bag with resin water mixture. Excess liquid is squeezed off and open-air dried or with fan-assist.

Table 2: Soy Protein Dry/Wet Resin, fiber substrate characteristics and fiber: soy binder ratios

Board #	Binder Type	Fiber Length (mm)	Binder %
25-27	dry resin	3-20	50%
28-30	dry resin	20-40	50%
31-33	wet resin	non-woven mat	40%
34-36	wet resin	non-woven mat	50%
37-39	wet resin	non-woven mat	60%

Ecovative Mycelium Binder

The incubation profile for mycelium growth on coir fibers was determined by researchers at Ecovative that took into consideration the nutritional composition, weave type and density of the coconut substrate as well as the required temperature and humidity conditions during incubation. Prior to incubation, coconut fiber substrate was sterilized using 3.5% hydrogen peroxide, or autoclaved (120°C, 15 psi for 55 minutes). Incubation of coconut fiber substrate with mycelium occurred over a period of 7 days within a polyethylene bag within a temperature and humidity controlled chamber. Nutritional augmentation of sterilized micronutrient mix WB N007, developed by Ecovative, was used to add sufficient carbohydrate and trace minerals to naturally deficient coir substrate. After growth period, coconut fiber-mycelium mixture was left to dry in the open or heated to stop further growth.

Table 3: Fungal Mycelium, fiber substrate characteristics

Board #	Biobinder Type	Fiber State	Fiber Treatment
40-42	mycelium	bagged, long fibers	H_20_2
43-45	mycelium	bagged, short fibers	H_20_2
46-48	mycelium	non-woven roll	H_20_2
49-51	mycelium	non-woven roll	autoclaved

Thermal Pressing Conditions

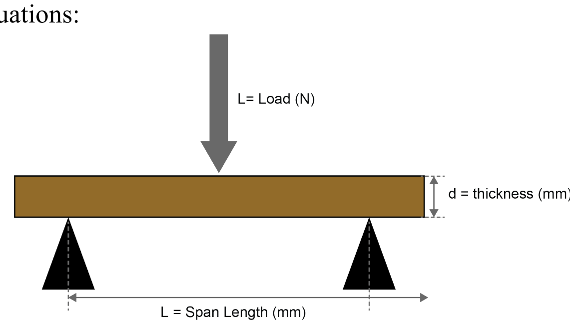
Temperature, pressure and duration conditions for thermal pressing have been well understood and optimized within each biobinder industry (refer to Table 4).

Table 4: Thermal Pressing Conditions for each biobinder

Binder #	Temp (°C)	Pressure (psi)	Time (mins)	Source
Pith	135-150	350-500	8	FAO2003
Soy	110-130	350-500	6-8	e2e
Mycelium	165	350	5	Ecovative

Flexure Testing

After pressing, boards were allowed to cool down in a metal jig at 20°C and 50% relative humidity. Three samples were cut from the central region of each ¼" thick pressed fiberboard into 2" x 8" testing specimens. The span for each test was 6" and loaded at the center of the span with a 5kN load cell. As stipulated by ASTM D1037, the speed of the load is applied at a uniform rate of 0.12-0.12 in/min (3-5mm/min) depending on thickness of the specimen. The dimensions and weight of all three test specimens were determined using a vernier caliper (accuracy ±0.3%) and an analytical balance (accuracy of not less than ±0.2%. The oven-dry mass of the sample was, obtained after drying a specimen at 103±2°C until a constant weight is reached. The load-deflection data was recorded by an Instron testing machine until the maximum load is achieved. Testing was performed in replicates of three and deflection was measured at the mid-span point using a tensometer attached to the base of the testing jig. The modulus of rupture and apparent modulus of elasticity were calculated for each specimen using the following equations:



$$E = \frac{L^3}{4bd^3}\frac{\Delta P}{\Delta y} \quad (1) \qquad R_b = \frac{3P_{max}L}{2bd^2} \quad (2)$$

Where E = apparent modulus of elasticity, psi (kPa)
L = length of span, mm,
b = width of specimen, mm,
d = thickness of specimen, mm,
$\Delta P/\Delta y$= slope of straight line portion of the load deflection curve (N/mm)
P= maximum load (N)
R_b = modulus of rupture, psi (MPa)

Calculation of Strength - Cost Performance Ratio of Coconut Fiberboards

The cost of coconut fiberboards made from biobinder units are compared to wood and reconstituted wood products. The cost per unit is based on the cost of raw materials, including coconut fibers and biobinder, and production costs that include biobinder, energy and labor rates informed by manufacturing partners, e2e Materials and Ecovative. The price of coconut fibers is assumed to be USD $0.38 per pound, which is an average cost from a survey of suppliers. The board density is determined from the optimum mechanical performance for each biobinder. In evaluating the strength – cost performance, in accordance standard material property characterization, which takes into consideration the influence of inflation and units of currency, the formula relative cost per unit volume is used. The cost of steel is assumed to be USD $0.30/kg.

$$CvR = \frac{\text{Cost/volume of material}}{\text{Cost/volume of mild steel rod}} = \frac{\text{Cost/ kg x density of material}}{\text{Cost/kg x density of mild steel rod}}$$

RESULTS AND DISCUSSION

Coconut Fiber and Pith Morphology due to Husk Processing

Micrographs of coconut fibers had porous 'tube-like' 10µm openings with an internal matrix of smaller tube-like pores. Compressed and uncompressed pith showed significant differences in their surface area and surface geometry. While compressed pith showed comparatively ordered pores of openings between 30-40µm, loose pith binders had tissue-like pore sizes resulting in an advantageous increased varied, surface area. As a result compressed pith resulted in insufficient binding between coconut-pith layers.

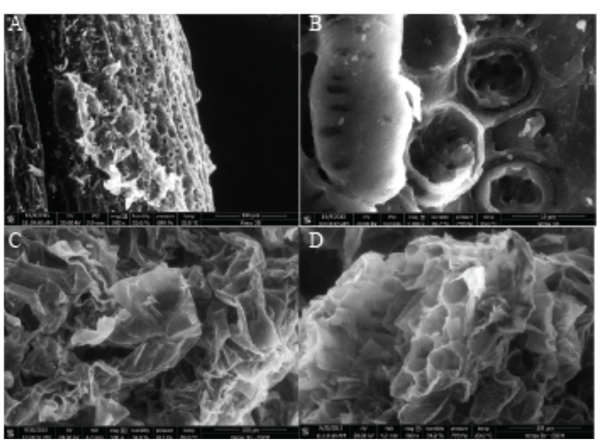


Figure 4: SEM Micrograph of (a) Rolanka Bristle Coir Fiber with remnant pith tissue (b) Openings in Rolanka Bristle Coir Fiber Surface (c) Uncompressed Pith Tissue from Ecofibers (d) Compressed Pith Tissue from Rolanka

Effect of Fiber Length and Mat Density on Flexural Strength

Coconut fiber length played a critical part in determining contact area of fibers with the biobinder. Longer fiber lengths resulted in larger gaps in the fibrous matrix resulting in the settling of pith and soy at the bottom of the fiberboard matrix during pressing and a highly non-uniform distribution of binder across the fiberboard section. For the soy biobinder, the non-woven needle-punched mat demonstrated the highest flexural strengths, while the longer fiber length of 20-40mm demonstrated higher MORs than 3-20mm. Fungal mycelium growth largely did not occur throughout loose fibrous bags of 3-20 and 20-40mm coir mixtures. Added water and supplement nutrient solution to aid mycelium growth settled at the bottom of bags. Inoculation of coconut mats in rolls with higher nutritional profile, demonstrated significantly uniform growth. While this method was successful, autoclaving was necessary to ensure the absence of any competing microbial activity that would result in mold development during growth period. Hydrogen peroxide sterilization was not effective and resulted in growth of mold in segments of the coconut mat substrate. The uneven density of the coconut fiber mat also resulted higher growth of mycelium in denser regions which higher MOR performance. Therefore quality control of the coconut mat substrate's density is critical to mycelium board's mechanical performance. The difference in MOR values between the most and least dense coconut-mycelium fiberboards were approximately five-fold.

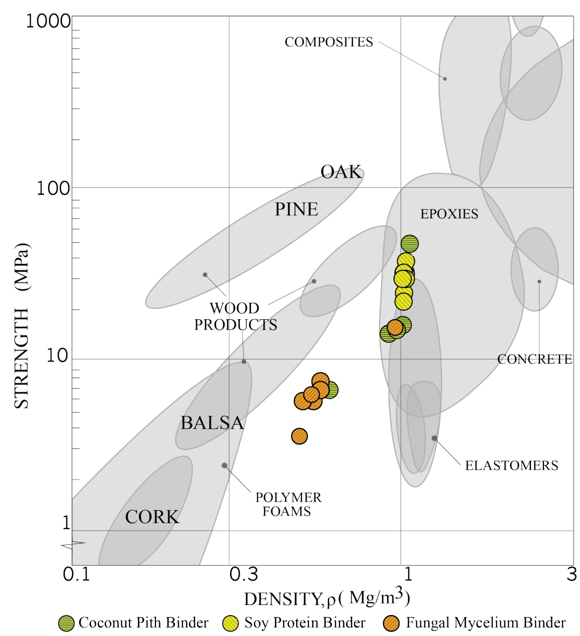


Figure 5: Ashby Chart Comparison showing Coconut board Flexural Strength over Density

Effect of Fiber-Binder Ratios on Board Mechanical Properties

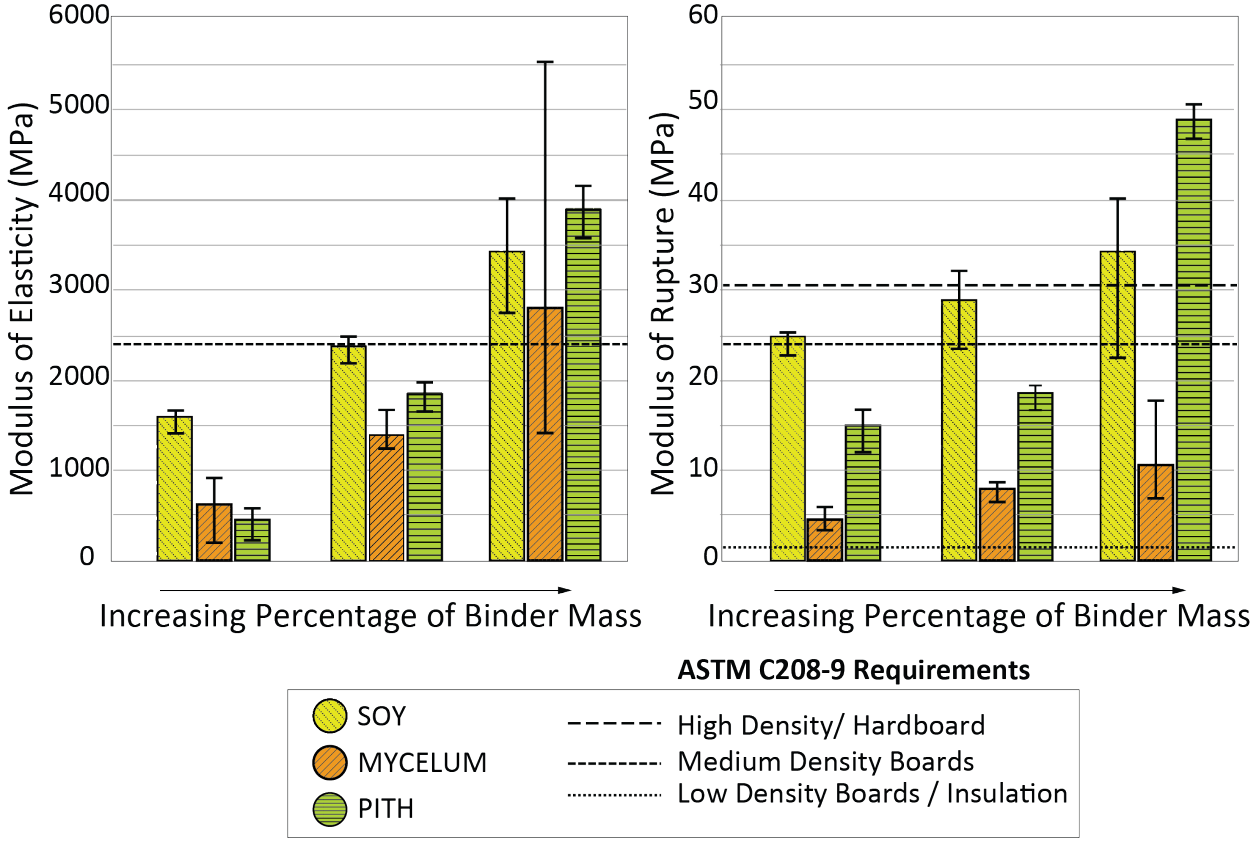


Figure 6: Graph showing Increasing Binder Ratio on Board Modulus of Elasticity and Modulus of Rupture

Fiber binder ratios were seen to play the most significant role in the increase of board stiffness and strength. While increase of pith ratio from 30% to 90% demonstrated an approximate 300% increase in flexural strength, its MOE increased form 170-1840 MPa. Within fiberboards bounded by soy resin, where recommended binder ratios are close to 50%, small increases of binder ratio from 50% to 60% showed almost a doubling of flexural strength.

Mechanical Performance and Economic Cost Comparison Coconut Fiberboards with Competing Products

Coconut fiberboards made from soy binders offered the best resistance to deformation (42.4MPa) per unit cost, relative to pith and mycelium bounded boards. However the cost of processing raw coconut pith binder ($0.09/kg), which eliminates the cost of pre-treatment like sterilization, wetting and drying, cost half that of soy processing and mycelium biobinders.

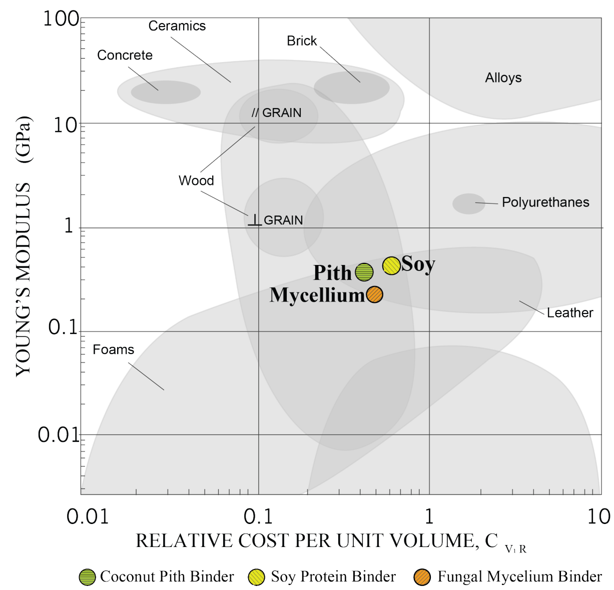


Figure 7: Ashby Chart Comparison Young's Modulus over Relative Cost per Volume

CONCLUSION

The mechanical performance of coconut fiberboards and biobinders show potential to compete across engineered wood markets, particularly in the low to medium density market. Continued studies optimizing thermal pressing conditions and more efficient fiber-binder contact pre-processing show potential for high-density board applications if the cost structure of production remains closer to the costs afforded by coconut pith processing costs. Further studies investigating promising pre-processing and biobinder preparation techniques, such as open air-drying of wet biobinder on non-woven coir mats, shown in the soy-biobinder experiments, show high potential to improve the mechanical performance in pith bounded boards. However while the assumption was that uncompressed raw pith material cost the least (USD $0.86 per kg), relative to the e2e Material's soy binder (USD $0.90) and Ecovative's mycelium binder (USD $0.97), the transport of loose, uncompressed pith material from source contexts to manufacturing facilities needs to be considered. Potential opportunities to drive down production costs, could involve the substitution of biobinder and fiber components with cheaper agricultural by-product particle-based materials. Further research into coconut fiberboard coatings and emerging bioresin surface treatments need to be explored in the context of high humidity and pollutant exposure conditions, common in hot-humid urban environments.

Today the cost of agricultural waste like coconut fibers are still 2-3 times more expensive than raw material feedstock for the engineered wood industry, including wood shavings and saw dust. While coconut fiberboards can be competitive with low to medium density products on the market today, market projections need to capitalize on the unique properties of coconut fiberboard towards other building material applications such as thermal, acoustic and low-energy 3D molding that render such products competitive within high-value applications.

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