Form Follows Fiber: A Case Study for a Low-Carbon Bioplastic Chair

PROTOTYPING METHODS IN BIOMATERIALS MANUFACTURING

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A selective transition from conventional plastics, metal, and timber to renewable bioplastics presents significant opportunities for curbing emissions and landfill loads. When bioplastics are blended with crop fiber, an abundant waste product of agriculture, they make resilient composites that can displace the plastics and monoculture lumber in engineered timber. In this case study, an ergonomic task chair is built from scratch using experimental biomaterials and digital prototyping methods. Historically, the chair has been the platform to experiment with new means of production in a discourse over emerging technologies and novel materials. This "Fiber Chair" is free from petroleum ingredients, made from more than 98% biomaterials, completely compostable, and has a fraction of the footprint of conventional competitors. Three different molding processes are prototyped and discussed in detail (compression, lamination, and injection) to explore the challenges and opportunities in transitioning to bioplastics in the building trades. Results from early sample testing and life cycle assessments are shared with consideration given to future applications.

Keywords: Sustainability, Materials, Manufacturing, Prototyping, Low-Carbon

1. INTRODUCTION

Since the industrial revolution, manufacturing practices have prioritized speed, scale, and the financial bottom line, rather than the health of the environment and its inhabitants. Industry's over-extraction of natural resources, open-loop production models, and the reliance on fossil fuels have led to skyrocketing carbon emissions and the proliferation of toxic waste (Stuchtey, 2020).

This project proposes a low-impact production model without the externalities of non-renewable source materials. A modern, ergonomic task chair is built from scratch using experimental biomaterials and is as free from petroleum as possible. Various molding techniques are required to manipulate the ingredients into a comfortable, stable, three-dimensional form. At the outset, the key research questions were:

- What are the major challenges in prototyping and achieving dimensional accuracy?
- How does the performance and environmental impact compare to conventional analogs?
- How scalable are these methods of production?

2. LITERATURE REVIEW AND MARKET ANALYSIS

2.1 OVER-EXTRACTED

Fossil fuels and their byproducts are essential to modern industry; from plastics to adhesives, paints and lacquers, packaging, and the rivers of fuel that support global trade. Plastics are prized for their consistent properties and strength-to-weight ratio, rendering them cheap, abundant, and versatile (Stuchtey, 2020). However, over 40% are disposed after one use and take hundreds of years to break down, infiltrating our planetary systems (Lau et. al, 2020). Our use of these materials is responsible for 8% of carbon emissions and is projected to triple in less than seventeen years (Stuchtey, 2020). This global dilemma is an entanglement not easily unraveled. Fossil fuel subsidies and inexpensive drilling leases keep the cost of virgin plastic artificially low, a practice whose justification stems from plastics' pivotal role in economic activity (Packard et. al, 2019). Extractors and manufacturers have never borne the material's full cost, as their emissions, recovery, and decomposition tolls are paid for by our planet. With over 400 million tons being manufactured globally each year, less than 10% will be recycled and less than 5% will reach the market for a second time (Sullivan, 2020).

Given the sins of the plastic industry, one logical reaction is that we should double down on timber as a substitute. After all, it is more rapidly biodegradable, sequesters carbon, and is already used in thousands of different applications. In fact, this is exactly one of the provisions of Net Zero, the international initiative to curb carbon emissions by 2050 - replacing energy intensive materials with timber substitutes (IEA, 2024). According to market analyst Jason Mitchell (2022), "producing one ton of wood absorbs a net 1,700kg of carbon from the atmosphere, over and above the energy expended in growing, harvesting and processing it." Using timber is therefore a carbon sink! What could go wrong?

One word – demand. As the world's population expands and migrates to cities there will be skyrocketing demand for timber building materials for housing and infrastructure, cardboard, palettes, paper pulp products, heating fuel, and much more asked from the humble tree. Projections for 2050 are up to four times our current demand, raising questions of where all this lumber will come from (Mitchell, 2022).

Currently, just 13% of global forests are sustainably managed (WWF, 2023). To meet demand, biodiverse regions are being converted to monocultures like eucalyptus, bamboo, rubberwood, and spruce (Elias & Boucher, 2014), pushing out workers who made a living from the land for generations (WWF, 2023). Housing and building materials like wood-based panels, composites, and sawnwood will drive much of this demand for timber, and being so competitive, has the greatest impact on lumber pricing (Elias & Boucher, 2014). Timber for engineered lumber, like OSB and Plywood, is often harvested from vulnerable areas and then soaked in petroleum-derived adhesives that off-gas formaldehyde and other VOC's (Zhang et. al, 2017).

2.2 THE OPPORTUNITY OF BIO-COMPOSITES

Bioplastics are a collection of materials derived from plants rather than petroleum. They are usually made by extracting sugar from a feedstock like corn, soy, or sugarcane (Gibbens, 2018). Currently, bioplastics make up just 1% of plastic produced annually, used mostly in bottles, utensils, and textiles, so there is a large opportunity to expand their use (European Bioplastics, 2020).

There are compelling advantages, foremost being that bioplastics decompose at varying rates, breaking down into soil components and water (Hoornweg & Bhada-Tata, 2012). Some estimates project it could lower the sector's emissions by up to 70% (Gibbens, 2018). Economically, the growing of feedstocks is an agrarian activity that decentralizes opportunity and provides income for low-skilled labor in many regions around the world (Bioplastic Feedstock Alliance, 2015). However, there are challenges. Aside from the higher cost, manufacturing bioplastic could lead to produce being diverted from a community's food supply. This may exacerbate scarcity issues in periods of drought or raise the price of agricultural commodities (Bioplastic Feedstock Alliance, 2015). It may entice farmers to deforest extra land for agriculture (Narancic et. al., 2018), divert water for irrigation, or use more fertilizer and pesticides (Bioplastic Feedstock Alliance, 2015). Presently, the weight of these risks is low, as only .02% of the world's agricultural land is used for growing bioplastic feedstocks (European Bioplastics, 2020).

2.3 INSPIRATION AND MARKET ANALYSIS

Designers and manufacturers are responding to the call with innovative methods of working with natural materials. Hemp, a durable crop that can thrive in poor conditions and sequesters carbon, can be combed into batting to be used in insulation or mixed with lime to make "hemp-crete" (Hempitecture, 2024). A rediscovery of straw-bale construction is underway in contemporary architecture, due to its low carbon footprint and excellent heat-retention and acoustic properties (Carr, 2022). Similarly, "mass-timber" skyscrapers have broken ground in several cities around the world as a more sustainable alternative to steel superstructures and reinforced concrete (Mendez, 2022).

3. METHODS AND PROCESSES

3.1 DESIGN

To target both plastics and timber in a complicated designed object, yet still speak to commodity-scale, the search for an application led to furniture, and naturally, a chair. Since the 19th century in Western Modernism, the chair has been the platform to experiment with new means of production in a discourse over emerging technologies. Inspired by designers like Thonet, the Eames, Eileen Gray, and Walter Panton (Phaidon Editors, 2013), the chair celebrates process and authenticity. However, could a low-carbon chair be beautiful, and not just look, smell, and feel like sitting on a straw bale?

A portfolio of materials would be required, composed of renewable bioplastics, naturally dyed textile, and waste crop fiber. Three molding processes were considered in the form and CMF exploration. Flat "straw-boards" made for strong parts that performed well in compression; a logical choice for legs and struts. Laminated panels made for elegant sheets that could sweep through space and define chair seats and backs. Injection molding served as a versatile process to make hard-wearing joints that could withstand many cycles of use, moderate flex, and high loads.

Figure 1. Bio-composite Samples. Jute Textile, Straw, Plant Starch, Rice Starch, Gelatin, Sugarcane, Paper, Madder Root. Photograph.

A chair tuned for use in a convention hall seemed most appropriate, as any environmental benefits would be magnified by the number of chairs. It should keep the sitter upright, poised for tabletop tasks or attending a lecture, while offering a gentle lean for relaxation and contemplation. A human factors study led the chair's dimensions and compound curvature.

3.2 COMPRESSION MOLDING (THE FRAME)

Compression molding binds fiber in a matrix with an adhesive, much like OSB. A common analog is a waffle press – mix your "batter," fill your mold, and press into shape. It has a higher fiber ratio than other molding processes, and lends itself to large, simple forms. Controlling both the fiber and the adhesive allows for more precise calculation of environmental impact.

Making bioplastic requires at least a starch and water and its properties can be altered with the application of heat and the addition of plasticizing, foaming, or cross-linking agents (Dunne, 2018). A variety of cheap, household goods can be used to make natural, compostable adhesives, including rice, corn starch, vegetable oil, gelatin, and flour. These binders are an important piece, because they can make up more than 50% of a material's mass.

Fiber was processed to various lengths, from 2 inches down to 25 thousandths of an inch and natural dyes were used as colorants. Over one hundred samples were tested for strength and moldability with consideration given to how they sand, cut, take a drilled hole, and hold a screw. A laser cutter was used to route panels from a flat pattern and locate screw holes. Beeswax and carnauba wax was used to finish the parts.

3.3 LAMINATION (THE SEAT)

For the chair seat, a process was required that could achieve graceful, three-dimensional geometry and target the polypropylene, plywood, and fiberglass in conventional chairs. Inspired by the Eames chairs of the 1940's, paper and textiles were laminated over various forms. Alternating the grain direction of these substrates improved the stiffness, with applications of bio-resin in between each layer. A bio-"resin" is a broad category of materials that mimic a thermosetting polymer and sets into a solid with exposure to a hardener or oxygen (Dunne, 2018).

A CNC router was used to cut the negative of the form into an open-mold, assembling smaller sections to achieve a Z-height of >12". Sanding the surface smooth and finishing with polyurethane and carnauba wax lent a nonstick surface for part removal. Burlap, a hard-wearing textile of woven jute dyes well, is resistant to pilling, and has a slight cushion. Layers are draped over the mold, impregnated with resin, and rolled by hand to promote adhesion. Offcuts were used to reinforce certain areas, hiding recycled fabric between the dyed outer layers. An array of plants was used for the natural dye stocks, rather than synthetics, and include indigo, madder root, weld, and walnut husk.

3.4 INJECTION MOLDING (THE FITTINGS)

A final process required for the chair was the production of small, very strong parts for brackets, shocks, and feet. An FDM 3D printer was used to create jigs for drilling holes, prototype the parts, and test assembly. For "production" pieces, a manual, single-shot machine was constructed, which allowed for the freedom to use bio-based feedstock and other additives. Using an SLA 3D printer, molds were created from high-temperature resin that can withstand thermal shock and cycling. The molds have vents, a gate, and is housed in an aluminum frame for rigidity and clamping. PLA was used primarily, derived from sugarcane that is commercially compostable (Narancic et. al., 2018).

4. RESULTS

The chair was assembled using bio-composite parts produced through the methods described above and fastened with metal hardware. The bioplastic composites make up 98.2% of the chair's mass and result in a low energy intensity due to their regional production model (Wahl, 2016).

Using a single-factor LCA method (White, St. Pierre, & Belletire, 2013), the Fiber Chair has an **environmental impact score of 17.55**. Common incumbents were also evaluated; an aluminum and polypropylene chair scored 33.93 (or nearly 2X higher); and a plated steel and fiberglass chair scored and 48.62 (or nearly 3X higher). A lower score means better (or less) environmental impact. Material utilization is near 100%, as waste from manufacturing or breakage can be reground and fed into new parts without quality degradation. It was produced in a facility powered by renewable energy.

Figure 2. Build Process; Clockwise from top left: Adhesive Preparation, Seat Lamination, Structure Samples, Prototype Construction, The Fiber Chair v1 (Madder Root Dyed Jute Textile, Recycled Fabric, Straw, Plant Starch, PLA, Metal Fasteners). Photographs.

5. DISCUSSION

There are many perspectives through which the chair's production can be evaluated.

5.1 MOLDING PROCESS AND DIMENSIONAL INTEGRITY

The chair is comfortable and has a slight flex in the lumbar – a result of the stiffening performed in the lamination of the seat. It is uniquely textured, which reflects the materiality of the source ingredients. Structural performance was adequate, but could be improved with further iteration and load testing. The most significant challenge in all three molding processes was the evacuation of moisture. Samples would not harden until enough moisture was removed, a process which continued for days after demolding. This leads to shrinkage and warp – altering the sample's surface finish and limiting dimensional stability. In injection molding, fiber was added in various ratios to accelerate decomposition and lower the material costs. Adding fiber raised the bioplastic viscosity and made it harder to fill the mold, yet it beautifully speckled the transparent part. The fiber choice did not seem to matter as much as the binder, as all samples have failed along lines of adhesion, not fiber tear. This is beneficial, as the fiber can be harvested from more resilient intercropped plants rather than a monoculture.

5.2 DESIGN FOR LONGEVITY

The parts were finished with a beeswax topcoat to improve durability. However, it could be desirable to have a more hydrophobic sealant. Water-based polyurethanes or greenguard-certified paints may provide low-VOC off-the-shelf solutions (EWG, 2024). The chair's collapsible design and metal fasteners allows compact shipping and disassembly for repair and storage. At end of life, the natural ingredients used in the bio-composites ensures they may be composted in a short time-horizon.

5.3 LIFE CYCLE ASSESSMENT AND ENERGY AUDIT

The prototype of the chair was evaluated using the single-factor LCA framework from IDSA's Okala Method (White, St. Pierre, & Belletire, 2013). Ingredients for each part in the bill of materials was weighed and scored according to their primary and secondary manufacturing processes. 51.7% of its impact score comes from the textiles and starches used in the adhesive, so that is an area for further refinement. The chair was produced in a facility powered by a combination of hydroelectric and solar energy. The results for the chair were compared to similar task chairs composed of aluminum/plastic and plated steel/fiberglass, as shown in Figure 3. The same scoring process was conducted, with Disposal and Transportation steps included.

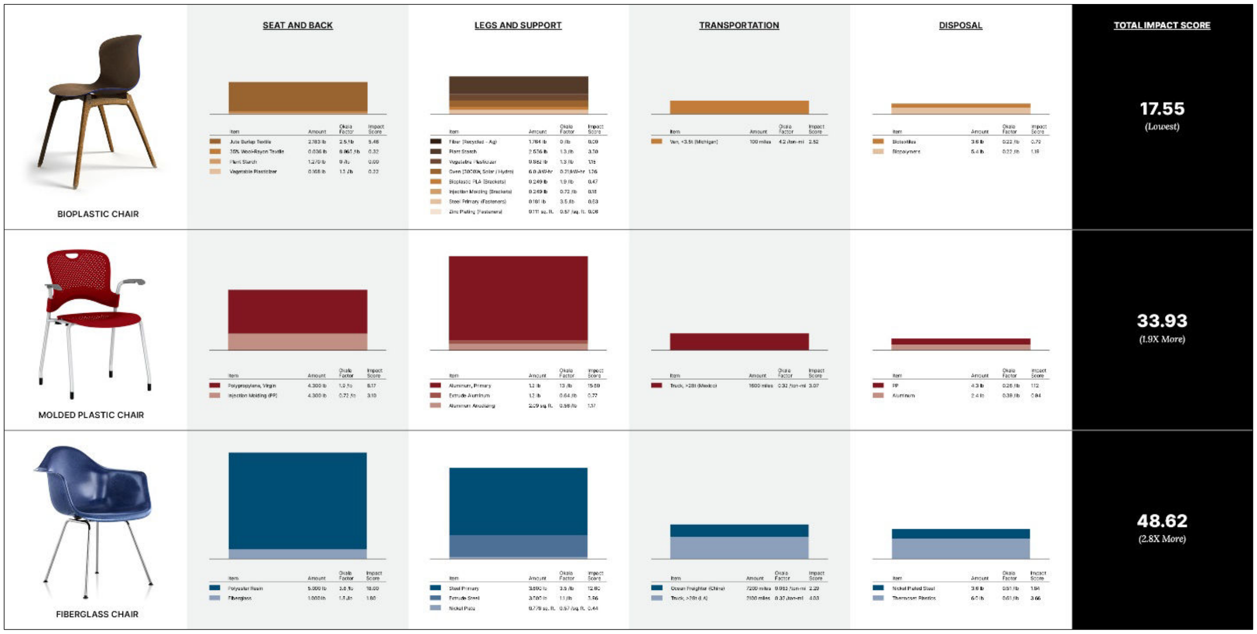

Figure 3. Excerpt from Life Cycle Assessment of the Fiber Chair Prototype v0.3. Infographic.

5.4 MATERIAL UTILIZATION

The Chair Seat supports the collection of waste materials and funds the growth of plants that promote biodiversity and ecological resilience. Recycled textiles can be used in the lay-up for reinforcement, such as recovered and damaged denim and cotton, concealing them between the dyed and higher-quality outer layers. Use of these materials in this fashion diverts them from the landfill. Including polyester, however, would hinder the product's compostability and was excluded (Biodegradable Products Institute, 2023). The natural dyes used in the seat fabric were derived from walnut husk, indigo, madder root and weld, and lend bold colors to the seats with unique variations in hue and tone.

5.5 CROP SELECTION AND BIODIVERSITY

Securing a variety of raw, waste, and bioplastic materials will yield a range of options to account for regional diversities in ecology and labor specialization. Grasses and cereal crops are a renewable fiber source with a much shorter time-to-harvest than trees. They are well suited to fiber diversion because they are perennial, typically grown without chemicals and irrigation, have deep root systems, sequester a high amount of carbon, and need to be mown to stimulate the plant's growth each season (Keyser et. al, 2015). Harvesting fiber every other year provides a good alternative to burning because it would sequester carbon, rather than releasing it (Keyser et. al, 2015). As discussed, the diversion of food crops for use in bioplastics is concerning. An alternative would be to target land unsuitable for growing food. Industrial fiber, starch, and dye plants could be sown to remediate soil and provide seasonal pollinator habitat. Land with poor soil, contaminants, pests, or an arid microclimate could make for good sourcing sites (The Land Institute, 2024). Some plants, like alfalfa, sunflower, floral dye, and cover crops could be sown to fix nitrogen, uptake heavy metals, promote biodiverse habitats, or boost carbon levels to improve the soil (The Land Institute, 2024).

6. CONCLUSION

This case study proposes three low-carbon production methods and lends insight into some major challenges facing the discipline. Integrating waste crop fiber into engineered lumber products could ease demand for virgin timber, while use of renewable bioplastics and recycled textiles could displace petroleum plastics and their byproducts. Finding affordable, natural substitutes for compounds like PVA glue, synthetic paints, and polyurethane open up a wide possibility of building materials and colorants.

A next step for this research is the development of building materials that could displace those which are environmentally damaging or hazardous to human health. A wide and expanding range of biomaterials will be evaluated, from other plant starches, to algae, mycelium and even bacteria. Additionally, there are other applications in structural packaging, healthcare, apparel, household goods, and appliances. With more development, regional biomaterials can be a viable alternative to industrial production with non-renewable resources. Expanding use of these materials could dramatically lower the environmental footprint of consumer goods and supply chains.

7. REFERENCES

Biodegradable Products Institute. (2023, March 03). *Compostable Products.* Retrieved March 03, 2023, from https://bpiworld.org/composting

Bioplastic Feedstock Alliance (2015, November). *BFA White Paper: Responsible Bioplastics*. Version 10. Retrieved from https://bioplasticfeedstockalliance.org/resources/

Carr, Belinda. (2022, June 17) *How to Build Straw Bale Houses | Pros and Cons.* [Video]. Youtube. https://www.youtube.com/watch?v=W7_LfVF2qSg

Dunne, Margaret (2018, July 14). Bioplastic Cook Book. *FabTextiles*. Retrieved from https://issuu.com/nat_arc/docs/bioplastic_cook_book_3

Elias, Pipa and Doug Boucher. (2014, October). *Planting for the Future. Union of Concerned Scientists*. Retrieved from https://www.ucsusa.org/sites/default/files/attach/2014/10/planting-for-the-future.pdf

Environmental Working Group. (2024, April 18). *EWG's Healthy Living Home Guide – Wood Stains and Finishes*. Retrieved April 18, 2024, from https://www.ewg.org/healthyhomeguide/wood-stains-and-finishes/

European Bioplastics. (2020, February). *Bioplastics Market Data 2019*. Retrieved from https://www.european-bioplastics.org/wp-content/uploads/2019/11/Report_Bioplastics-Market-Data_2019_short_version.pdf

Gibbens, Sarah. (2018, November). What You Need to Know About Plant Based Plastics. *National Geographic*. Retrieved from https://www.nationalgeographic.com/environment/article/are-bioplastics-made-from-plants-better-for-environment-ocean-plastic

Hoornweg, Daniel and Perinaz Bhada-Tata. (2012). *What a Waste: A Global Review of Solid Waste Management*. WorldBank. Retrieved from https://openknowledge.worldbank.org/handle/10986/17388

International Energy Agency. (2024, April 18). *Net-Zero by 2050 – A Roadmap for the Global Energy Sector*. Retrieved April 18, 2024, from https://www.iea.org/reports/net-zero-by-2050

Hempitecture. (2024, April 18). *About Hempitecture*. Retrieved April 18, 2024, from https://www.hempitecture.com/about/

Keyser, Patrick, Craig Harper, Gary Bates, Ray Smith, Tom Keene, and Chris Lituma. (2015, December). *Using Prescribed Fire to Manage Native Grass Forages in the Mid-South*. University of Tennessee Center for Grasslands Management. Retrieved from https://extension.tennessee.edu/publications/Documents/SP731-J.pdf

The Land Institute (2024, April 18). *Learn – Frequently Asked Questions*. Retrieved April 18, 2024, from https://landinstitute.org/learn/frequently-asked-questions/

Lau, Winnie, Yonathan Shiran, Richard M. Bailey, Ed Cook. (2020, September). Evaluating scenarios toward zero plastic pollution. *Science*. Retrieved from https://www.science.org/doi/10.1126/science.aba9475

Mendez, Edgar. (2022, June 02). Is a mass timber construction boom coming to America? *Fast Company*. Retrieved from https://www.fastcompany.com/90756578/is-a-mass-timber-construction-boom-coming-to-america

Mitchell, Jason. (2022, November 09). Net zero could drive up the global demand for timber, putting at risk the world's forests. *Investment Monitor*. Retrieved from https://www.investmentmonitor.ai/features/net-zero-drive-up-global-demand-timber-forests/

Narancic, Tanja. (2018, August). Biodegradable Plastic Blends Create New Possibilities for End-of-Life Management of Plastics but They Are Not a Panacea for Plastic Pollution. *Environmental Science and Technology*. Retrieved from https://pubs.acs.org/doi/10.1021/acs.est.8b02963

Packard, Lauren. (2019, February). You're Paying for Plastic Pollution. Center for Biological Diversity. *Medium*. Retrieved from https://medium.com/center-for-biological-diversity/youre-paying-for-plastic-pollution-af80c3567be5

Phaidon Editors. (2013). *The Design Book*. New York, NY: Phaidon Press.

Stuchtey, Martin. (2020). *Breaking the Plastic Wave*. SystemIQ and Pew Charitable Trusts. Retrieved from https://www.pewtrusts.org/-/media/assets/2020/07/breakingtheplasticwave_report.pdf

Sullivan, Laura. (2020, September). How Big Oil Misled the Public Into Believing Plastic Would be Recycled. *NPR*. Retrieved from https://www.npr.org/2020/09/11/897692090/how-big-oil-misled-the-public-into-believing-plastic-would-be-recycled?sc=18&f=1001

Wahl, Daniel Christian. (2016). *Designing Regenerative Cultures*. Axminster, England: Triarchy Press.

White, Phillip, Louise St. Pierre, Steve Belletire. (2013). *Okala Practitioner: Integrating Ecological Design*. Phoenix, AZ: Okala Team.

World Wildlife Fund. (2023, March 03). *Timber*. Retrieved March 03, 2023, from https://www.worldwildlife.org/industries/timber

Yang, Jianlei, Yern Chee Ching, and Cheng Hock Chuah. (2019). Applications of Lignocellulosic Fibers and Lignin in Bioplastics: A Review. *Polymers (Basel)*. Retrieved from https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6572173/

Zhang, Xiaochun, Yuding Zhu, Youming Yu, and Jiangang Song. (2017, July 03). Improve Performance of Soy Flour-Based Adhesive with a Lignin-Based Resin. *Polymers (Basel)*. Retrieved from https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6432244/