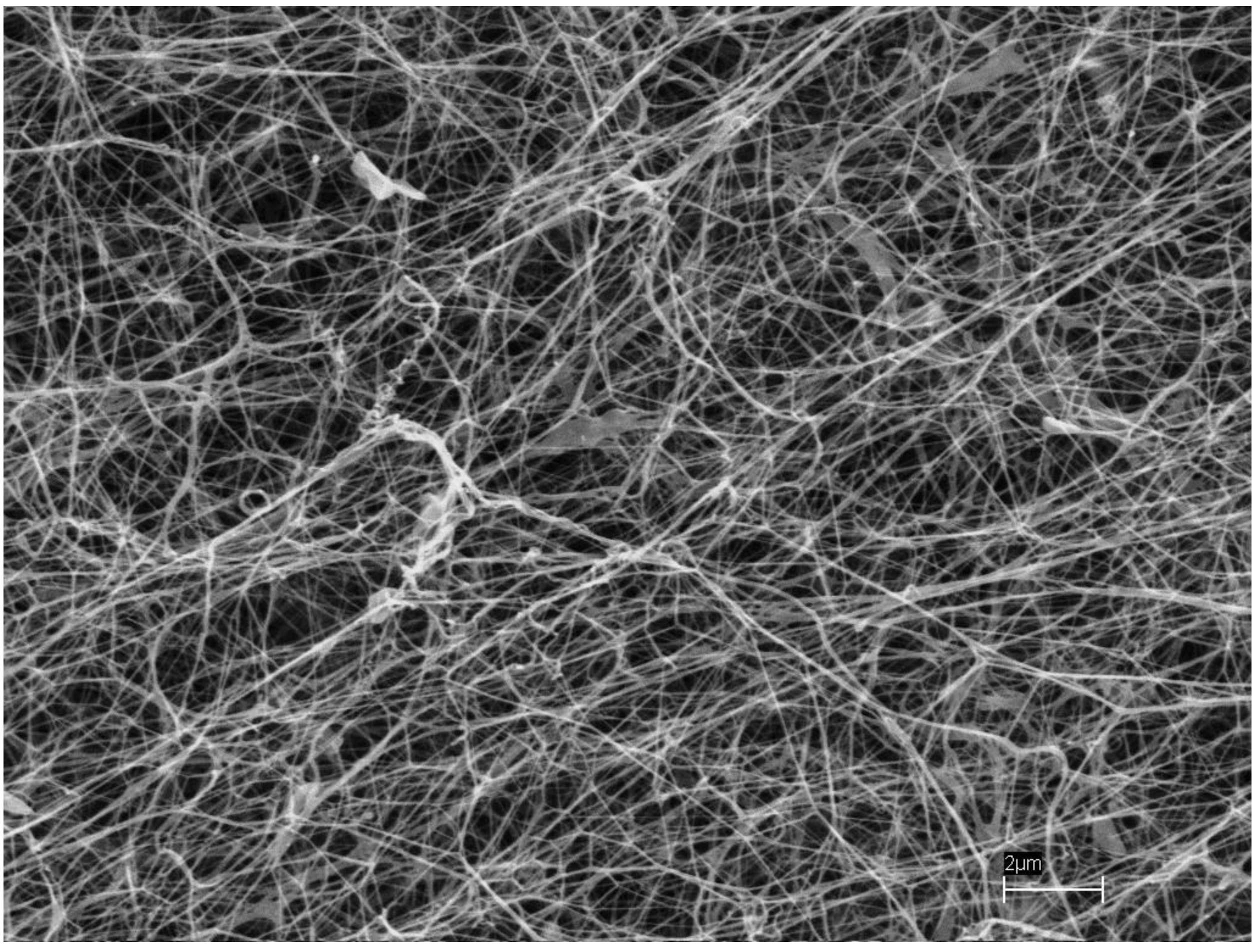
Investigation into Polyhydroxybutyrate and Bacterial Nanocellulose Composites for Single-Use Paper Packaging

Better Biomaterials - ENGR 4020 / GSVS 3020

Alec Brewer
Cutter Grathwohl
Ryan Crosser
Wyatt Black

May 6th, 2021



An image of Bacterial NanoCellulose fibers via SEM by A. Stanisławska

Project Executive Summary

This project aims at developing a novel, hybrid biomaterial that could take the place of plastics and paper products. Industrial ecology is one of the overarching goals that we want to strive towards. The ability for our products to be derived from waste products of other industries and after their use be able to biodegrade non-toxically back into the environment, each of which contribute to our product's circularity, will be the central theme of this project. This project will also investigate what it means to be sustainable. In today's climate suitability has become a buzzword that industries use all the time to convey a sense of responsibility and ingenuity, however, it is commonly misused. To define it in the most overarching way sustainability has come to include this idea of balance between three areas of performance: economic, environmental, and societal, which is known as the "triple bottom line" (Carter & Rogers, 2008). Economic sustainability consists of supporting long-term economic growth without negatively impacting social, environmental, and cultural aspects of society. Social sustainability is defined by the use of resources in a manner that allows current and future generations to create healthy and livable communities, i.e., to prosper. Promoting opportunities for today's society without compromising the opportunities of future generations and communities. Environmental sustainability includes the responsible harvesting of both renewable and nonrenewable resources. Renewable resources must be harvested at rates that allow for regeneration. While non-renewable resources must be harvested at rates that allow time for human invention and investment to develop alternatives. Waste emissions must be kept within the assimilative capacity of the environment without degrading future assimilative capacity or other uses.

Our team will strive to meet requirements in all three areas. However, if the product is environmentally and socially viable but not appealing from an economic standpoint, the product will fail. During the process of identifying our problem space, we have found a few key qualities that a good solution will need. The solution space we will explore is one that is holistically (economically, environmentally, and socially) sustainable and has similar or better qualities to existing products. Our solution must guarantee a smaller footprint over the course of its life cycle, produce less pollution, and have a smaller impact on the environment. Financially, the solution has to be affordable, either with a small, acceptable increase in price, or ideally, no increase in price or even a savings when compared to the current consumer behaviors as they currently exist, and an overall increase in accessibility/equity. Through personal experience and stakeholder discovery, we have learned about the challenges associated with broad market changes in consumer behavior as such, traditional consumer waste practices will reinforce our sustainable objectives.

To accomplish our goals the team has come up with a set of hypotheses that will hopefully bring us closer to a stronger and more durable hybrid product that either component could do on their own. Our first hypothesis is that the addition of BNC fiber to Kraft/OCC paper blends will increase the strength of the resultant paper. The basis for this hypothesis is BNC's higher length to width ratio allows for increased bonding in plant fiber boundary interticies and as a result allows more hydrogen bonds to form between the larger Kraft and recycled fibers (Bajpai et al, 1970; Johansson, 2015). This will be tested by using the Instron machine in the

BME IDEAS Lab. Samples will be tested until failure in order to find their tensile strength. The second hypothesis is that the addition of a PHB coat will increase the water resistance properties and also not hinder the biodegradable properties. This will be investigated by performing water permeability tests to determine the wetting angle of our material. This data will be used to compare the wettability of our material to other established materials. These two tests will allow us to quantify key metrics identified last semester which were informed by industry standards.

Business Case

Executive Summary

Better Biomaterials is a UVA Engineering capstone project group that works in conjunction with Transfoam LLC and Kombucha Biomaterials LLC to develop more circular packaging and materials options.

Waste-derived Polyhydroxybutyrate (PHB) and Bacterial Nano-Cellulose (BNC) are fully biodegradable materials that have a lower footprint and higher functionality than their less sustainable counterparts. We are testing these materials in conjunction to create sheets of treated, enhanced-strength consumer packaging solutions. Our materials will be tested in accordance with various ASTM, ISO and TAPPI standards, namely ASTMD4600, ISO 14855, etc. biodegradability standards.

Mission Statement

Better Biomaterials aims to disrupt traditional paper and plastic packaging manufacturing by providing a more holistically sustainable option for packaging products. We focus on all aspects of production from sourcing sustainable to end of life recovery in order to promote a greener and more circular economy.

Vision Statement

Institutional investors are starting to recognize the importance of sustainability in businesses. This is driving a current need for sustainable packaging that Better Biomaterials hopes to fill with packaging options that are sourced and consumed sustainably for an overall more sustainable product than quick fix alternatives.

Core Competencies

Our team shares a passion for sustainable/resourceful innovation and complementary knowledge in R&D of papers, plastics and packaging. This lends itself to our core competencies listed below:

- Sustainable sourcing
- Research and development in sustainable materials
- Novel material solutions
- Designed with consumers and end of life in mind
- Minimizing environmental impact of packaging options

Business Model Canvas

Key Partners

Suppliers: Locally sourced products reduce carbon emissions associated with transportation

Adopting Companies: Working together to minimize negative environmental effects in their manufacturing processes not to offset the benefits of the new biomaterials

Key Activities

Research and Testing of new Biomaterials and their applications to expand biodegradable product applications

Material Production, of PHB, Bacterial Cellulose, and their combined derivative

Partnership/Sales of produced materials to packaging companies

Key Resources

- Styrene oil derived PHB
- Waste Kombucha derived bacterial cellulose
- Intellectual Property
- Lab space for production of materials
- Workers

Value Propositions

Help companies to achieve their sustainability goals by incorporating the entire materials lifecycle to minimize overall environmental impact

Minimal retooling and change to production lines due to overall material similarities to existing packaging options

Customer Relationships

Sales group reaches out to potential clients, typically warm leads met at conferences

Providing material samples to test within their manufacturing facilities

Channels

Attending packaging and materials conferences to connect with potential clients

Word of mouth between regional companies to minimize transportation related environmental impact

Customer Segments

Companies that specifically produce packaging that is then sold to other companies

Companies that produce their own specific packaging in house

Emphasis on “green markets” and developing markets

Cost Structure

Costs of Goods Sold: $2800/ton
Includes: Equipment and Infrastructure (varies by scale); Purchase materials at $2000/ton; Energy requirements: $400/ton, Labor $400/ton

Selling, General & Administrative: Sales and Marketing $100,000; Research and Development $300,000; Legal and Professional Services $5,000
Capital Expenditures: Building first pilot plant $9,000,000

Revenue Streams

Sales of material, Price TBD*

- PHB – $4500-$5200/ton
- Dry fiber bacterial cellulose – ~$40,000/ton

Licensing of Intellectual Property for production of materials

Market Research/Size

We began this investigation by reaching out to subject matter experts within the packaging and materials industry to get their insights and feedback on where our product would fit into the market. The four main conversations that we conducted and their major insights are as follows:

Richard Fine - Founder & CEO of Biopak

- Discussed regulatory barriers to primary food contact packaging
    - No recycled fiber is qualified for food packaging due to contamination concerns
    - Helped define areas where regulatory guidelines were accommodating to the unique value proposition for BNC and PHB enhanced products and materials
- Identified key distinctions in terminology for biodegradable, backyard compostable, and industrially compostable and how it technically relates to industry practices and marketing

Chip Blankenship - Former CEO of GE appliances

- Importance of differentiating our value proposition to companies
- Highlighted the importance of money in companies making the decision to invest in or adopt our material

Michael Hawboldt - Sourced Products Quality CBT Team Lead at GE Appliances

- Discussed the important differences between large company adoption vs small company adoption of our material
    - Large companies are more likely to invest into R&D or a company that has potential
    - Large companies are driven by institutional investors who hold large chunks of their stock. These institutional investors are looking to measure businesses on their sustainability going forward. This means that these companies are setting strategic goals that revolve around sustainability and will be spending a lot of money to achieve those goals in coming years

Gayle Schueller - Senior Vice President and Chief Sustainability Officer of 3M

- Echoed the value in our thoughts around targeting up and coming markets that might be more environmentally friendly
- Also added that emerging economies are another long term adoption option since they are still developing infrastructure and this means they can develop infrastructure to be ready for the future as opposed to currently leading economies where they have existing infrastructure that makes it harder and more expensive to upgrade

In summary, after consulting subject matter experts in packaging and upon initial market analysis targeting there exists a subset of the single use packaging market that relies on coated paper and would benefit from the unique value propositions offered by PHB and BNC. Further investigations divulge that a narrower subset of coated paper, specifically cannabis packaging is the exemplary target product to break into the packaging industry. This analysis is constructed below and is underpinned by: the newly established legitimacy and growth of cannabis combined with industry and consumer sentiment aligned with sustainability. The combination of these factors creates an opportunity for new sustainable paper packaging in the nascent cannabis industry.

Example Market Analysis:

Total available market: Single-use packaging market (Mordor Intelligence, 2020)

- The total value of coated paper packaging was $34.3 billion in 2020
- Year-on-year growth of 6% will continue to grow steadily as the industry projects $47.3 billion in annual revenue by 2026

Serviceable available market: Coated paper packaging market (Markets & Markets, 2017)

- The total value of coated paper packaging is ~$7.2 billion million in 2021
- Year-on-year growth of 3.2% will continue to grow steadily in the next decade

Serviceable obtainable market: Cannabis packaging market (Chrzan, 2019)

- The total value of cannabis packaging was ~$493 million in 2019
- Year-on-year growth of 24% will drive this value to $1.63 billion in 2024

Design Idea Generation and Selection

External research

Our early external research focused on paper products and challenges in the packaging industry. Then BNC and PHB as material additives for external packaging were examined for specific benefits offered. Finally, a decision matrix was formed to semiquantitative assess important end product deployments using BNC and PHB while considering sustainability aspects unearthed from research and interviews with third party experts and stakeholders. The results of the decision matrix determined that paper packaging liner board (known as Kraft liner board) was the ideal single use product case.

Packaging

The world of packaging can be segmented into three levels (Heck, 2019):

1. Primary packaging: the inner enclosure that is in direct contact with the product itself (e.g. a bottle filled with wine)
2. Secondary packaging: the outer emballage and filler material designed to contain multiple primary packages and maintain their original condition (e.g. a carton enclosing multiple bottles of wine)
3. Tertiary packaging: this consolidates multiple primary and secondary packages to facilitate handling, transport, and storage (e.g. a pallet)

DHL, a multinational express mail service company in Germany, conducted a survey of their largest 800 partners and found that demand for sustainable packaging and public awareness of packaging waste were the top trends shaping packaging strategy (Heck, 2019). These trends can be seen in *Figure 1*. Today there are signs that packaging is struggling to meet society's changing needs. In particular, existing packaging systems are being tested by three major trends:

1. The rise of e-commerce and direct-to-consumer delivery
2. The growing need for packaging convenience and a delightful customer experience
3. Pressure to improve sustainability, reduce waste, and eliminate pollution from packaging material

The rise of ecommerce, amplified by the Covid-19 pandemic, has resulted in a dramatic increase in direct-to-consumer shipping amidst this industry's focus on sustainable product implementation. Traditionally, packaging has performed three critical roles:

- Protection against loss or damage in the supply chain journey
- Transportability facilitating cost-effective handling and storage which promotes efficiency in the supply chain
- Communication providing relevant information to supply chain participants, from warehouse pickers to delivery couriers and end recipients

Figure 1: Displays trends from DHL Packaging Survey highlighting both packaging customers and end customers emphasis on high performance and sustainability (Heck, 2019)

Mechanical performance such as tensile strength, burst strength and smoothness are the critical criteria influencing the aforementioned roles of packaging. Additionally, these are also the technical factors that begin to diminish below performance thresholds with increased recycled fiber. Increasing recycled fiber content in packaging is a proven practice for increasing sustainability which uses current manufacturing infrastructure. Thus increasing higher proportions of recycled fiber in paper packaging while maintaining performance employs technology and fiber recovery chains already established and a solution that the packaging industry is clamoring for. Furthermore, these performance standards are also increasing as seen in recent trends of consumer product distribution.

The increased demand in packaging combined with regulatory and consumer demand for sustainable packaging has created pressure on packaging to evolve, adapt, and implement changes rapidly and at a wide scale. While paper packaging has existed since antiquity and the first cardboard seen as early as 1817, modern paper packaging is the result of decades of manufacturing improvement such as the advent of recycling. (Attic Storage, 2020) Once again a revolution is occurring spurred by e-commerce and demands improved performance. An e-commerce package is handled 20 times more frequently on a journey from the warehouse to the consumer's home than when it is transported on a pallet to a retail store. Each touchpoint is an opportunity for item damage. As a result, e-commerce supply chains require packaging robustness and product protection. As an example showcasing the reorientation of packaging requirements, brick-and-mortar retailers typically require packaging to be drop tested from five different angles; while, leading online retailers ask for 18 separate drop tests (Heck, 2019). Alongside protective properties increased emphasis is surrounding advertising on packaging. In direct-to-consumer sales packaging has undertaken a dominant role as a primary form of physical customer interface and printability is essential property for eye popping advertisements required to stand out amid this crowded space. Clearly, paper packaging (plastic coated and uncoated) is in need of dramatic innovations that will improve sustainability while maintaining and improving mechanical properties for protection and customer satisfaction. Below are two biobased polymers that offer unique solutions to packaging based on their sustainable aspects, mechanical improvements, and implementability in current manufacturing practices.

PHB and BNC as a Solution

Misuse and end of life mismanagement of consumer packaging materials is one of the biggest threats we face to the health of our planet. The average use of paper plastic packaging is only a few days, yet together in the environment many of these materials persist hundreds of years beyond their usable lifespan.

Single-use plastics and plastic coatings are of particular concern due to their indefinite persistence and tendency to fragment into toxic microplastics. When ingested by animals and humans, microplastics cause crippling defects and cancers. Microplastics' rapid accumulation throughout the food web and infiltration of drinking water systems threatens the survival of nearly every species on earth. Fear of these repercussions is forcing a paradigm shift in the materials used in single-use products.

PHB is a bio-based plastic that offers the same durability, barrier properties and shelf life as petroplastics, except it does not pollute the environment. PHB's complete biodegradation is expedited by light and microbial activity, allowing it to degrade in as little as 12 weeks in both terrestrial and marine environments. PHB's rapid, nontoxic degradation is unmatched by any material of the same durability currently offered in consumer products, and will facilitate the degradation of treated paper waste in both the compost pile and the environment.

PHB Manufacturing is Expensive and Unscalable

PHB manufacturing depends upon plant-based raw materials, which have proven prohibitively costly and unscalable. The growth and processing of plants for PHB production requires toxic fertilizers and volatile solvents, contributing significantly to ocean runoff and eutrophication of waterways. Further, the time-consuming nature of agriculture and multi-step fermentation have created a bottleneck in raw material acquisition. The resulting competition for raw material acquisition, especially due to pandemic-driven supply chain disruptions, has driven prices even higher, and restricts full-scale production. Altogether, these factors have hindered PHB's widespread introduction to consumer markets.

Our Approach Unlocks Green, Scalable PHB Manufacturing

We will recycle plastic waste to produce PHB, providing a beginning AND end of life solution to global plastic pollution. Upcycling is a modern approach to waste management, which is the repurposing of waste into new materials or products of better quality and environmental value. Using genetically engineered microorganisms, Transfoam upcycles waste plastic into PHB.

Bioplastics have emerged as a strong candidate to replace many conventional petroplastics. Unlike most bioplastics that rely on thermal degradation, Polyhydroxybutyrate's (PHB) rapid degradation is driven by microorganisms and plants that use PHB as an energy source. As a result, PHB has the unique ability to degrade into only CO2 and water upon disposal. Facilitated by sunlight and compaction, this process occurs visibly in as little as six weeks without the need for industrial composting. When used in conjunction with other biopolymers, PHB increases the durability and biodegradability of these materials. PHB's widespread introduction to consumer products will significantly reduce the global footprint of bioplastic composting and plastic waste mismanagement; however, the industry's growth is limited by manufacturers inability to meet growing consumer demand.

PHB can be used in isolation or in a blend. The introduction of our recycled PHB to biopolymer blends will help bioplastic distributors and molders meet volume demand, improve performance and reduce costs. Polymer blends have grown increasingly popular due to their increased performance, namely in terms of pliability and reduced degradation time. PHB enhances performance in both these categories, which will accelerate its certification and integration into markets with an existing demand for sustainability.

Bacterial NanoCellulose

Bacterial NanoCellulose (BNC) fibers offer distinct material properties such as high length to width ratio, high water retention, high crystallinity index, high purity, and customizable surface chemistry that are unlike plant-based cellulose. These unique properties make BNC an intriguing candidate as an additive for reinforced paper composites. The chemical structure of BNC is identical to its plant counterpart which is typically purified during the Kraft process. Specifically, BNC is a linear polysaccharide chain consisting of D-glucose units connected by beta-linkages on the order of hundreds to thousands of units long (Crawford, 1982).

Structure

BNC fiber structure is ultra fine and ribbon-shaped with a width of 0.1-0.01 micrometers (obtained using SEM) or approximately 100 times thinner than plant cellulose (Bäckdahl, Henrik et al, 2005; Abitbol, Tiffany, et al., 2016). While orders of magnitude finer than plant cellulose fiber, BNC fiber exhibits similar fiber lengths of around 2-0.1 mm when compared with plants fiber lengths ranging from 2-0.8 mm (Choi et al, 2020; Ververis et al, 2003). Due to the extremely fine nature of BNC, the polar fiber possesses a high water retention two to three orders of magnitude larger than typical plant cellulose fibers (Karippien, 2017; Ververis et al, 2003). Additionally, the crystallinity index is higher (67-96%) (Andritsou et al, 2018; Dima al et, 2017). This crystallinity index is attributable to the purity of BNC. There also exist other nanoscale cellulose fibers derived from plant matter that exhibit similar nano properties which are typically referred to as microfibrillated cellulose (MFC). It has been the topic of much interest, experimentation, and commercialization attempts (discussed below); however, since MFC is plant derived cellulose, it initially contains other biopolymers such as lignin, hemicellulose, and pectin.

Kraft Processing

Typically, plant matter undergoes a purification process known as the sulphate or Kraft process used to remove the biopolymer impurities lignin, hemicellulose, and pectin to produce paper pulp. This purification aspect of the Kraft process accounts for 50% of the pulping operation's energy consumption. At the magnitude of this industry the Department of Energy estimated that for the United States in 2006 500 trillion BTU's (an energy equivalence of 90M barrels of oil) was used for chemical preparation and recovery in the pulping process alone (Jacobs, 2006). While chemical recovery has improved, noxious chelating agents, chlorates, and dioxins can still be discharged in effluent from pulp mills which disproportionately affect local communities such as Covington, VA which possesses the highest toxic inventory release in the state as described in our previous submission. In 2015, the Environmental Protection Agency (EPA) estimated that the paper and pulp industry accounted for 20% of all toxic air emissions in the United States (EPA, 2017). Compounded on top of the energy and environmental costs, the chemical refinement also degrades the cellulose reducing yield by up to 50% (EPA, 2017; Broten, 2012). The implementation of small quantities of BNC to the paper manufacturing process could foreseeably reduce the environmental burden plant matter pulp conversion carries, extend the longevity and proportion of recycled fibers in paper while producing mechanically improved end paper products.

Mechanical Property Improvements

Current limitations surrounding increasing concentrations of recycled fiber in paper packaging is related to the fiber quality degradation experienced by recycled fibers. During the process fiber length (one of the major contributing factors to paper quality) is reduced. These shorter fibers produce weaker and rougher paper which experience trouble with printing and exhibit lower burst, tensile, and compressive strength. The addition of MFC or BNC in relatively small amounts (0.5-3% dry weight) to paperboard has been demonstrated to increase burst, tensile, and compressive strength while increasing paper smoothness which aids printability. This result due to the unique fiber length to width ratio and high degree of polymerization exhibited by the fiber that allows more hydrogen bonds to form between the larger Kraft and recycled fibers.

In 2020, Balea et al. demonstrated that the addition of 2% dry weight addition of MFC to sheets produced from reconstituted OCC displayed an 40.3% and 46% increase in tensile index and burst strength respectively. Bajpai et al. also demonstrated the addition of 3% MFC by dry weight produced OCC derived board with a 60% increase in tensile strength showed that BNC when blended in quantities as low as 0.5-1.5% dry weight with typical plant fiber paper slurries demonstrates an increase in maximum tensile index of 5-25% (Bajpai et al, 1970; Johansson, 2015). Under TAPPI T 494 a sheet of 107 GSM must exhibit a tensile strength no lower than 5.6

(kN/m) (Goyal, n.d.). Success will also be determined by the percentage of OCC pulp vs Kraft pulp with a 1% dry weight BNC addition. Any increase of OCC fiber beyond 50% would provide benefit but higher proportions provide greater economic and environmental return. Burst strength for a similar pulp proportioned liner board should be no lower than 250 KPa for a 186 GSM as tested by TAPPI T 403 Bursting Strength of Paper (Goyal, n.d.). Treatment with 0.5% dry weight MFC for paper created by Torvien showed an entire order of magnitude reduction in roughness measured by Altisurf 500 profilometer; it should be noted that additional processing steps such as calendering (pressing the dry sheet through heated cylinders) were taken in conjunction with the MFC addition. (Torvinen, 2012) Successful implementation of a 1% dry weight BNC additive to a Kraft paperboard will achieve a smoothness of 1750 (mls/min) in accordance with TAPPI T 479 for a Test Liner (186 GSM) while increasing the OCC paper beyond 50% (Goyal, n.d.). There is overwhelming empirical evidence suggesting that minute additions of MFC and BNC can significantly alter mechanical properties important to paper packaging. Under these results and with an understanding of the unique fiber interactions BNC and MFC have throughout the cellulosic paper web it is not unreasonable to suggest that increased recycled fiber content (or lighter weight) products are feasible. Integration into current manufacturing methods and infrastructure is the best way to assure rapid adoption by the industry. Several challenges exist with integrating MFC or BNC into fourdrinier machines and the fiber processing method.

Manufacturing feasibility

Paper packaging is made at a daunting industrial scale. The papermaking industry is continuously challenged by different aspects: The increasing requirements of mechanical, physical, and printing properties to accomplish the high quality demand of paper products, the deterioration of the recycled fibers as a consequence of the increasing recycling rate, and the restrictions in the production costs (Heck, 2019). Concurrently, paper production is projected to grow from 422M metric tons in 2019 to 495M metric tons in 2030 (Statista, 2020). With increasing demands and narrow margins, major consolidation has been seen in the paper industry over the last two decades. With the need for sustainable solutions in paper packaging, turn-key innovations that require little additional investment in processing machinery or reduction in the rate of paper production lines (thus decreasing production capacity) are essential for adoption.

As mentioned before BNC contains a higher water retention than traditional Kraft paper. Typically, the limiting factor in line speed is water removal from the newly formed paper web. So, although BNC’s higher water retention is advantageous for some applications, at industrial scale paper manufacturing this is a challenge. Several experiments surrounding colloidal chemistry manipulation have addressed this issue. By manipulating slurry ionic charges through the addition of cations bound to MFC strength increased was achieved without negative impacts on dewatering time. Dewatering, defined by TAPPI T 221, is the time elapsed while draining water from a slurry of pulp through a paper formation mesh. While fourdrinier machine run rate is the best way to understand the impact of a fiber addition, TAPPI T 221 provides a small sample indication of fiber addition effects on a to scale paper operation. Internal examination by Kombucha Biomaterials has determined preliminarily that a 100% Sisal (common paper fiber) slurry of a 1L sample containing 0.016 g Sisal possessed a 95% dewatering time around 60 seconds. Currently industry dewatering times relating to pulps of interest for this project have proven hard to obtain. More tests in accordance with TAPPI T 221 will be required to determine an effective dewatering time for an 50% OCC and 50% Kraft fiber slurry. This value will be compared to various increased increments of BNC and OCC addition. Success would be indicated by similar dewatering times that are statistically significant between control samples and biomaterial additive infused samples.

Additionally, even dispersion of a fiber additive is critical to strong paper formation. Poorly dispersed web formation will actually lead to weaker paper. Quantification and manipulation of fiber disbursement via cationic colloidal chemistry and specialty fiber analysis while achieved by leading paper institutions may be outside the scope of our project in terms of quantification but deserve consideration and acknowledgement.

Commercialization of Similar Technologies (MFC)

Recent attempts have been made to create commercially viable MFC reinforced products that display the enhanced mechanical properties elucidated above. As described previously MFC is similar in structure to BNC and can elicit similar property enhancements to paper products produced with it. It is derived from wood pulp through energy intensive mechanical shearing and chemical treatment (Lu et al, 2020). Previously, this energy intensive process prevented economic deployment of MFC at a commercial scale. However, to meet market demand and policy changes, research institutes and European paper companies have taken significant steps toward commercialization. In a paper published by Zambrano et al. in 2020, a preliminary techno-economic assessment showed that the addition of MFC to tissue paper products could have a savings on a range of $77-149 per ton of end product (Zambrano, 2020). This case was made in that introducing MFC into a tissue paper was able to use overall less standard tissue fiber while maintaining product strength and performance. Findings showed that although better performance was attained with higher degrees of MFC, there was a limit at which the addition of MFC or the continued process refinement of MFC (which can improve nano properties but is an energy intensive thus economic process) did not produce more economic savings for the improved mechanical properties and reduction in other fiber (Zambrano, 2020). Currently, this study indicated the price of dried MFC to be $1,493 per ton. This amount represents a comparative price standard that our project can aim towards when evaluating scale up costs even though this economic analysis is based on a similarly related product of tissue paper. The study concludes mentioning that recycled paper products could benefit from the introduction of MFC additives where recycled fiber content is impeded by unsatisfactory mechanical performance. Several initiatives have taken place to introduce MFC to packaging specific commercial manufacturing.

European paper industry giants (Stora Enso, BillerudKorsnäs, and Borregard) have begun producing paperboard containing MFC on an industrial scale. Stora Enso in conjunction with BillerudKorsnäs has produced 500,000 tonnes of paperboard converted into lightweight milk cartons that will reduce the products' weight and save fiber (Williamson, 2017). This is significant since paper fiber is the highest capital expenditure for paper manufacturing. Even if production of MFC is relatively expensive, the small proportions in which it is applied to the end product may ultimately save money. Since this is cutting edge first phase trials cost structures remain closely held competitive secrets. However, investigation has shown that 9.1M euros have been invested to update mills and accelerate production while more than 100 million packages have been successfully produced (Williamson, 2017). Currently, estimates on MFC production range from 1,000-20,000 tonnes/year, the wide range reflecting the speculation and secrecy surrounding this technological advent. Since MFC is produced from plant matter it offers a large feedstock for raw material conversion that will become increasingly more economic with dedicated infrastructure to scale. Although, MFC must still undergo an intensified Kraft pulping process and harbors the negative consequences of Kraft pulping, unlike BNC which is naturally pure. The deployment of MFC in products indicates potential market viability for the premise of this project. Currently, there are sources of underutilized BNC that could be leveraged for deployment in papermaking.

BNC Sourcing

Kombucha is the fastest growing segment of the functional beverage market with a US market value of $556M with a +37% growth (Kombucha trends, 2017). Kombucha is a probiotic fermented tea. During the fermentation, a BNC pellicle forms at the liquid gas interface. This hydrogel consisting of nearly pure nanocellulose is often composted and could be obtained for free or little cost from Kombucha producers. Internal estimates from Kombucha Biomaterials place US BNC production between 13-20 dry tonnes annually (Grathwohl, 2019). Making some assumptions on trim, efficiency, and BNC proportion - 13 tonnes would produce over 3.5M - 1.5 cubic foot boxes at 250 GSM with 1% dry weight BNC. While this is a lower quantity than the 100M milk cartons that have currently been produced with MFC it is still a significant amount of material that is already consolidated among the largest Kombucha producers. Processing this Kombucha would require new infrastructure orders of magnitude and cost smaller than what is required for MFC. Additionally, processing would take place on site to eliminate unnecessary shipping costs and emissions. Other considerations would be sterilization of the BNC to prevent bacterial infection and transmission into paper production operations. Additionally, the low pH of the beverage would require neutralization for the BNC as acidity creates brittler and weaker paper that is undesirable for packaging applications (Williamson, 2020). These steps would be required to institute a standard material conversion process and at scale processing of Kombucha Scoby has currently never been attempted although internal estimates by Kombucha Biomaterials place water consumption at 4 times less than what is required to process an equal amount of hemp fiber (Grathwohl, 2020).

Other industrial sources of BNC exist such as Nata de Coco and Nata de Pina. Both are microbially fermented from coconut milk or pineapple juice to create a desert that is popular in Asian countries. Similarly, to Kombucha, Nata de Coco/Pina (Nata) are exhibiting growth at 5.6% CAGR (Bezinga, n.d.). Unlike Kombucha where the product is the broth with Nata the product is the BNC leading to increased effort toward scaling the BNC production and efficiency. This also leads to more expensive material acquisition costs. Costs of Nata BNC (retail $35K/dry tonne) are projected to be higher than Kombucha BNC; however, there is large commercial production with some producers creating 240 tonnes of dry cellulose annually (Wyk, 2018). Given these extra costs Kombucha BNC is the first principal target to maintain economic prudence while demonstrating manufacturing scale feasibility for BNC fiber.

With increasing interest in this space and the rise of biomanufacturing, there is increasing interest in utilizing other agricultural waste products as carbon sources for fermentation and BNC production. Current research suggestions span Corn Steep liquor, dregs from juice operations, wheat thin sillage, alcohol and diary byproducts to name a few (Carreira et al., 2011; Kurosumi et al., 2009; Zeng et al., 2011). As increasing policy pressure and consumer sentiment shift industrial producers could move to adopt these potential byproducts as feedstocks for the circular bioeconomy. This move would require large infrastructural investment and maintenance, but opportunities for growth in the biomass industry specifically relating to BNC appear abundant. Considering these immediate, low cost sourcing options provided from Kombucha along with actively growing industries like Nata and consolidated byproducts and effluents available from large scale agricultural operations, we deem BNC a worthwhile material to begin integrating into consumer packaging.

End of Life Impact

Cellulose is the most abundant biopolymer on the planet and biodegrades naturally in marine and terrestrial environments. BNC is no exception as in vivo degradation occurs through hydrolysis, microbial enzymatic, oxidation and physical mechanisms (Sukyai, 2020). A comparative study using Thermogravimetric Analysis (TGA) and an SEM evaluated degradation rates of PHB, BNC, and vegetal cellulose. All three materials were completely degraded with 160 of exposure to a natural soil environment (Schropfer, 2015). Additionally, through local outreach, Blackbear Composting in Charlottesville, VA has offered to conduct compost degradation studies of our materials individually and as a composite (withstanding pandemic restrictions). In terms of recycling and recyclability, the unique properties of BNC such as extreme water retention may influence downstream processing in recycling such as drying of the recycled fiber.

What follows is the selection process for generating the series of product ideas for the application of these two biomaterials for single-use packaging and items. Emphasis is placed on material acquisition, material properties, manufacturing applicability, and environmental impact. Alignment between the identified metrics and requirements for these materials and their conjunctive application is addressed as the innovative constituents for ten ideas that we deemed worthy of pursuit. The goal was for each team member to become knowledgeable on five or six of the ideas to be able to get as many eyes and different ideas as possible. The criteria that were prescribed for external research were current material flaws (MF), scale of volume global / national (GP), niche quantity (NI), Standards/ certifications/ industry norms (SC), Existing IP / Competitors (IP), and Potential Partners (PP). This research was used to create metrics and requirements for the decision matrix as well.

Top Product Ideas:

Key:

Current material flaws or underperformance (MF)
Volume global/national production (GP)
Defined niche market and niche quantity (NI)
Standards and certifications for industry (SC)
Existing IP / competitors (IP)
Potential partners (PP)

Shipping labels

- IP: purelabels.com already sells recyclable and compostable labels. Boldly claim to be the only company with labels that also have compostable adhesive (purelabels.com, 2020).
    - Other compostable shipping labels
    - Begs the question where is amazon in this? Are they making moves in this scene to integrate into their distribution chain?
- IP: zero waste shipping labels made completely from 100% PCW (post consumer waste) (Eco Enclose, 2020).
    - Printable, fully recyclable
- GP: If we assume that every package needs a label, with 103 billion parcels shipped globally per year, 103 billion labels are needed (Mazareanu, 2020).
    - Start with a specific target market/supplier of shipping labels

Clothing tags

- IP: Cotton tags are already compostable
    - But most are not made from cotton
        - Labels are usually made out of satin coated acetate which has a shiny finish and is flexible and durable. Other printed clothing labels are made out of similar materials to the clothing itself and include cotton, polyester, and nylon (Streditorial, n.d.).
- “Labels woven into the clothing are often made out of the fabrics taffeta, satin, and damask. These are normally shaped like rectangles and are commonly either 1 inch by 2 inches or 1/2 inch by 1 inch.” (as above)
- Clothing brands we could target (descending order of net worth)
    - Oscar de la renta, Louis Vuitton, H&M, Hermes, Gucci, Prada, Chanel
- SC: International Organization for Standardization (ISO) have their own labeling requirements that companies must follow if they wish to receive certification. Consumer protection agencies around the world have stringent care labeling requirements
- Big shift toward smart/digital/RFID labels in the industry to provide product authentication and asses tracking (Wnuk, 2020).
    - Since the beginning of this year (RFID) this technology has been used in over 10 billion labels, despite low market penetration reaching only 10 percent

Pizza box liners

- GP: “People are always shocked to learn that we throw away 3 billion cardboard pizza boxes every year in the USA (Lopes, 2020)”
- MF: “Pizza boxes are made from corrugated cardboard; however the cardboard becomes soiled with grease, cheese, and other foods once the pizza has been placed in the box. Once soiled, the paper cannot be recycled because the paper fibers will not be able to be separated from the oils during the pulping process. Food is a major source of contamination in paper recycling” (Stanford, n.d.).
    - MF: “This is now incorrect. It was decided in July that Pizza boxes are in fact recyclable, but like most things, this depends on the locality” (Murphy, Ebner, 2020).
    - Report from Westrock (Huge Paper Company - with site in covington, VA)
        - “If all pizza boxes were recovered for recycling, they would represent approximately 2.6% of the OCC stream or 2.2% of the OCC and mixed paper stream combined.”
        - “Pizza boxes currently found in the recycling stream have an average grease content of approximately 1 - 2% by weight level.”
        - “Grease is hydrophobic and when pizza boxes approach a 20 wt% concentration of the furnish, grease interference with inter-fiber bonding begins to result in significant paper strength loss (~5%). At pizza box concentrations under 10%, paper strength loss is low.”
        - “Therefore, there is no significant technical reason to prohibit post-consumer pizza boxes from the recycle stream.”
        - According to WestRock, 73 percent of the US population has access to recycling programs that accept pizza boxes (WestRock, 2020).
        - “The American Forest & Paper Association found that pizza-box acceptance is now <u>almost universal</u> among companies that manufacture from recycled cardboard” (Minter, 2020)

Pizza box lid table

- IP: Patent for one with an integrated cutter (Nelson & Andrisin, 2007).
- IP: Expired patent for original lid holder (Vitale, 1983).
- IP: Expired patent for a lid holder made of cardboard (Cohen, 1986).

Beverage Cartons/Cardboard boxes (water/milk)

- GP: Tetra Pak has $13 billion in annual sales (Taylor, 2019).
- IP: Tetra Pak are technically recyclable, but difficult to do (Path Water, 2019)
- IP: Tetra Pak cartons contain many layers containing plastic, paper, and metal (Tetra Pak, n.d.).
- GP: Boxed Water is already using a mostly plant based, paper carton. Claims both as selling points, might be willing to make the switch to a better plastic film (Boxed Water, n.d.).
- GP: Just Water is already using a plant-based plastic in its paper cartons. Also claims its cartons are recyclable. Still contains aluminum (JUST WATER, n.d. -a).
- GP: Just Water currently uses sugarcane based plastic. (JUST WATER, n.d. -b).
- MFC used currently in liquid containing paperboard packaging - in phase trials for scale up using MFC could possibly be a key to replace the thin barrier layers of plastics or aluminum which are often added to the otherwise renewable cellulose fibre-based

packaging

    - Stora Enso has focused initially on the liquid packaging board segment, being the first company to have successfully launched a commercial paperboard packaging including MFC. Since 2015, MFC has been used for source reduction and to improve board quality in dairy product packaging through its partner Elopak, a liquid food container manufacturer based in Norway (*Microcellulose Gains Foothold in Paperboard - Paper Advance*, n.d.).
    - "By using MFC, we get the maximum yield out of the raw material and thus more packaging material per ton of board. Important properties, such as stiffness and internal strength, are maintained, with less weight. Within Europe, there are various incentives and regulations to reduce the weight of packaging material. The partnership with Stora Enso makes it easier for us to reach these targets." Elopak has piloted the lightweight containers in the Eastern European market, offering it to all dairies in the region. More than 100 million packages have been produced successfully (Williamson, 2017).
- In touch with Beatbox and Just Water

Paboco bottle

- Biggest flaw is liner
- Develop 3 different generations of paper bottles
    - Stage 1 - slowly introduction to corporate practices
    - Stage 3 - completely paper with non-bioplastic liner
    - Working toward bioplastic liner, water-based ink, and paper cap
- Paboco site is working on whitewater closed loop system
- Piloting stage (scaling 2025 global manufacturing goal) price is premium
- Want to work with fast moving Consumer goods
- Use virgin fibers cause they’re strong and can be sustainably sources with authentication
    - Product type also too novel (primary packaging product) to justify material interaction with recycled fibers and food products for regulators
- Water based ink will be key (Michelsen, 2020).

Magic Spoon / Three Wishes Cereal boxes

- MF: Magic Spoon is a brand that sells upscale cereal at high prices targeted at young working professionals (Magic Spoon, n.d.).
- GP: No hard sales numbers, but growing and continuing to thrive despite the pandemic (Barkho, 2020).
    - Maybe a box isn’t the solution, maybe it is a reusable container?
    - Monthly subscription style is good for recovery, known volume, and more individual interest

ROOTS Restaurant Forks, Knives, Spoons

- 500 per case = 15 to 45 dollars per case (Webstaurant Store, 2020)
- 250 per case (biodegradable) = 100+ dollars per case (Webstaurant Store, 2020)
- Juice laundry only has 4 locations - buys from big box restaurant stores
- Single Fork 1000 per case = 40 dollars (Webstaurant Store, 2020)

- The biodegradable ones are made of PLA and meant to be composted
- Reached out to Roots and Juice Laundry - Both have sustainability initiatives

Kraft Liner Board

- SC: Existing standards range from 42 craft to 90 Kraft (DS Smith, n.d.).
- SC: Extremely well-defined specs/criteria for performance
    - All testing methodologies compiled with partners that can conduct institutional quality tests
    - In lab (UVA/KBM) testing (dewatering, compression, tensile) can be conducted ourselves
- (MF) Kraft liner board has an upper threshold limit on recycled fiber before printing is negatively impacted
    - Kombucha fiber would improve the smoothness of the paper and printing ability
    - Would increase Post-Consumer Waste (PCW) content leading to savings in raw material costs and shipping costs
        - Fiber is the largest cost in paper production; Kraft pulp being the most expensive
    - (NI) BNC doesn't require Kraft pulping like current MFC derived from wood pulp
    - The addition of 2 wt% of the cationic CNC increased the TI and burst strength of old corrugated containerboard (OCC) by 40.3% and 46%, respectively. Furthermore, the gloss increased notably and the roughness decreased (Balea et al., 2020).
    - The addition of 3 wt% of CNF produced from recycled cellulose streams increased the tensile index of recycled ONP and OCC by 30% and 60%, respectively (Balea et al., 2020).
- GP: BillerudKorsnäs has partnered with Norway's Borregaard, known as a biorefiner, to implement their Exilva brand MFC in paperboard products. BillerudKorsnäs' products include Kraft papers, sack papers, container boards and consumer product packaging. Based on the results of initial tests, the company has now decided on full scale trials with Exilva to start in early 2017
- Corrugated and Paperboard make up 35% of all packaging - meaning any properties/developments achieved would have a wide field of applicability and impact (New Indy Containerboard, n.d.)
- PP: NCSU, UW, Creapaper, New Indy

Niche Disposable Cup

- Often compostable paper/wax or PLA
- $.10-.20 /cup, 200-2000 per case
- Benefit from local and often relatively homogeneous stream collection

A Concept Classification Tree: A Summary of Ideas

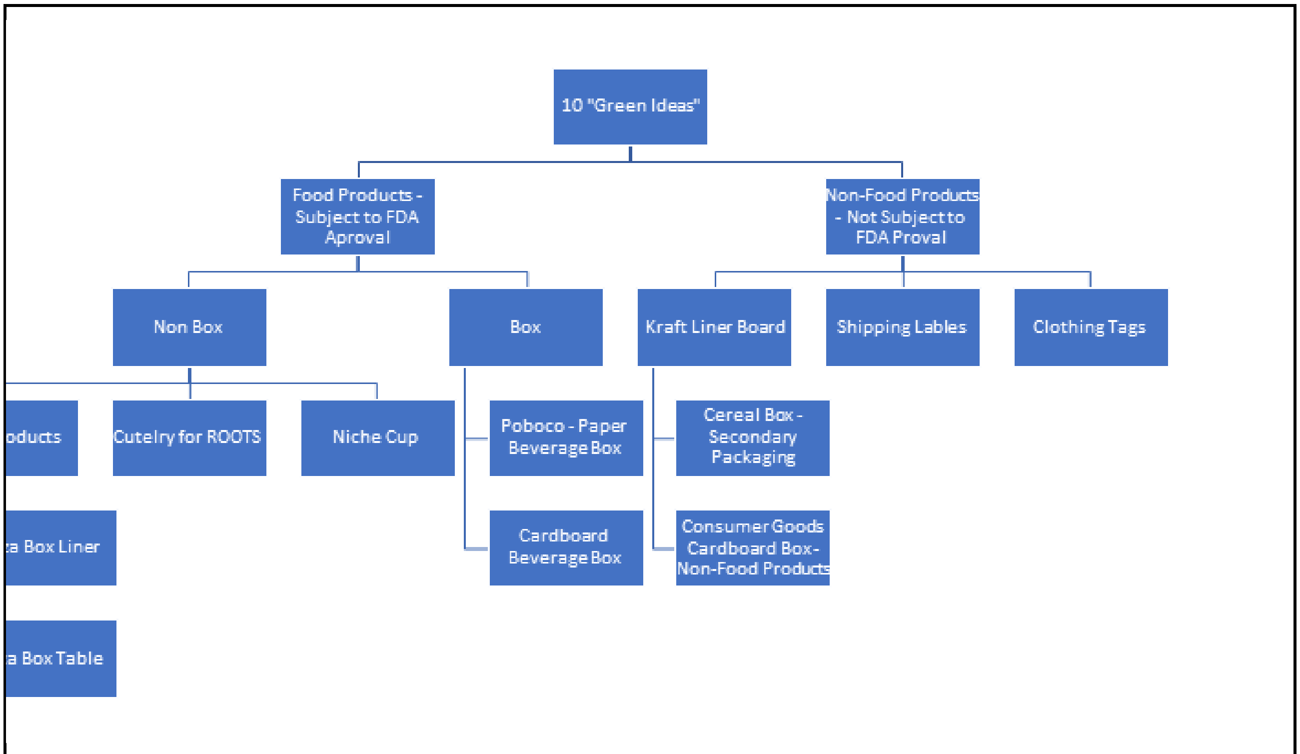


Figure 2: Initial Concept Classification Tree and categorization based on products and market segments identified.

Initial Concept Classification:

After going through our original group of ideas, classified in *Figure 2,* from the generation phase we agreed to move forward with the 10 most sustainable ideas presented here based on a combination of interest, impact, and perceived feasibility. Our initial break in grouping is between food and non-food items due to a broader consideration of FDA regulations being a much bigger barrier to the product development process. This leaves shipping labels, clothing tags, and Kraft liner Board as our most likely products because approval processes and regulations are extremely difficult to meet in the short term with limited capital.

Looking at the other side of the chart we included a division between boxes and non-boxes because of differences in material properties that are necessary to focus on down the line. Lastly, under the non-box category we have a few niche products that we feel could be great projects to partner with local businesses on to try and tackle their products and then adoption.

Decision Matrix Overview:

For the decision matrix each idea was ranked from 1 - 10, 1 being least important and 10 being most important based on the ability of the product to deliver on that requirement. The weighting is based on the “importance factors” on a scale of 1 - 5 (5 being most important) and we created the weightings by dividing one elements importance factor by the sum of the importance factors for headings in each table.

Idea	Burst Strength	Printable	Melting Point	Biodegradability	Shelf Life	Total Score (Weighted Average)
eight	0.227	0.227	0.136	0.227	0.182	
g Labels	1	10	10	6	10	7.04
g Price	2	10	7	10	8	7.40
ox Liners	1	2	8	9	2	4.18
ox Lid t	9	0	7	10	2	5.63
ge ard Boxes	10	10	8	9	10	9.49
ner Goods ard Box	10	10	9	10	10	9.85
, paper	10	10	10	6	10	9.08
Box	10	10	7	10	8	9.22
ilverware	2	2	10	10	5	5.45
ner Board	10	10	3	10	5	8.13
up	4	8	10	10	8	7.81

Figure 3: Mechanical Properties Matrix weighted according to material performance metrics to determine which products best aligned with our design requirements and respective testing methods normalized to the highest performing item in each category.

These mechanical properties, shown in *Figure 3*, reflect the most common physical properties that are required for shelf stability. Burst strength reflects the ability to hold what's inside, thus very important. Printability is very important because companies are going to want to cover the outside in labels and marketing information to drive sales and distinguish their brand’s use of a novel green packaging solution. Melting point is slightly less important since few consumers do anything above 180ºC; and while it is a consideration of the manufacturing process, it is also a physical property that is similar to existing materials.

Biodegradability is one of the most important factors because our goal is to create more circular packaging, and rapid, non-toxic biodegradation enables trash to assimilate into nature, which is cyclical in itself. Lastly, shelf life is important because products must preserve function after sitting on shelves, though shelf life of food service goods is relatively short compared to most industries.

Idea	Manufacturing Process	Product Cost	Consumer/corporate Adoption	Total Score (Weighted Average)
Weight	0.286	0.357	0.357	
Shipping Labels	9	2	3	4.36
Clothing Price Tags	8	4	5	5.50
Pizza Box Liners	8	4	2	4.43
Pizza Box Lid Support	8	4	5	5.50
Beverage Cardboard Boxes	10	5	10	8.22
Consumer Goods Cardboard Box	10	5	9	7.86
Paboco, paper bottlle	10	5	10	8.22
Cereal Box	6	6	9	7.07
Roots silverware	8	8	8	8.00
Kraft Liner Board	10	8	7	8.22
Niche cup	5	3	8	5.36

Figure 4: Logistical Considerations Matrix weighted according to logistical considerations to determine which products best aligned with our design requirements and respective testing methods normalized to the highest performing item in each category.

The metrics reflect the various stages and major factors in the manufacturing process displayed in *Figure 4*. From a company's perspective they want to keep changes as minimal as possible to mitigate risk and cost, so the weighting of these factors reflects that. Manufacturing process is about minimizing retooling and down times for the production lines, product cost is the ability to achieve a cost within a viable range of existing product cost, and adoption is how likely consumers and companies are to adopt our product based on how similar it is to existing products.

Idea	Recycling / Efficency	Raw Material Reduction	Ease of Use and Disposal	Total Score (Weighted Average)
Weight	0.250	0.330	0.417	
Shipping Labels	8	3	9	6.74
Clothing Price Tags	7	3	6	5.24
Pizza Box Liners	10	5	3	5.40
Pizza Box Lid Support	10	3	3	4.74
Beverage Cardboard Boxes	8	9	7	7.89
Consumer Goods Cardboard Box	8	10	7	8.22
Paboco, paper bottlle	8	10	7	8.22
Cereal Box	8	6	9	7.73
Roots silverware	10	6	4	6.15
Kraft Liner Board	10	10	10	9.97
Niche cup	10	8	9	8.89

Figure 5: Environmental Considerations Matrix weighted according to environmental footprint to determine which products best aligned with our design requirements and respective testing methods normalized to the highest performing item in each category.

These metrics reflect the various stages of life and the environmental impact displayed in *Figure 5*. Beginning of life being raw material reduction, middle of life being consumers ease of use and disposal, and end of life being recycling ability/recoverability. The weighting on these follows the formula listed above with the consumer ease of use and disposal being the most important category.

Idea	Mechanical Properties	Logistical Considerations	Environmental Considerations	Total Score (Weighted Average)	Final Rank
Weight	0.333	0.333	0.333		
Shipping Labels	7.04	4.36	6.74	6.04	T-8
Clothing Price Tags	7.40	5.50	5.24	6.04	T-8
Pizza Box Liners	4.18	4.43	5.40	4.66	11
Pizza Box Lid Support	5.63	5.50	4.74	5.29	10
Beverage Cardboard Boxes	9.49	8.22	7.89	8.52	3
Consumer Goods Cardboard Box	9.85	7.86	8.22	8.64	2
Paboco, paper bottlle	9.08	8.22	8.22	8.5	4
Cereal Box	9.22	7.07	7.73	8	5
Roots silverware	5.45	8.00	6.15	6.53	7
Kraft Liner Board	8.13	8.22	9.97	8.76	1
Niche cup	7.81	5.36	8.89	7.35	6

Figure 6: Summary Matrix representing the synthesis of weighted decision matrices respective of the environmental, mechanical, and logistical considerations that define our triple bottom line. These products shown in green gradient represent the best use cases aligned with our design requirements and biomaterials' unique properties.

For the summary matrix shown in *Figure 6*, we gave each group an equal weighting to balance out the increased complexity of some categories vs others instead of a total point weighting system. The factors are the three other matrices that we utilized to inform our decision, thus giving us our total scores and final rankings on the right. The team decided on the creation of a BNC additive infused Kraft liner board with a PHB coating based on the decision matrix findings. With this hybrid, Kraft liner board the team will be able to easily fall either into the categories of cereal boxes or consumer goods corrugated packaging highlighted by the new concept classification tree in *Figure 7*. What follows is the methodological process of sample paper sheet formation that adheres to TAPPI T 205 from various blends of OCC, Kraft and BNC fibers.

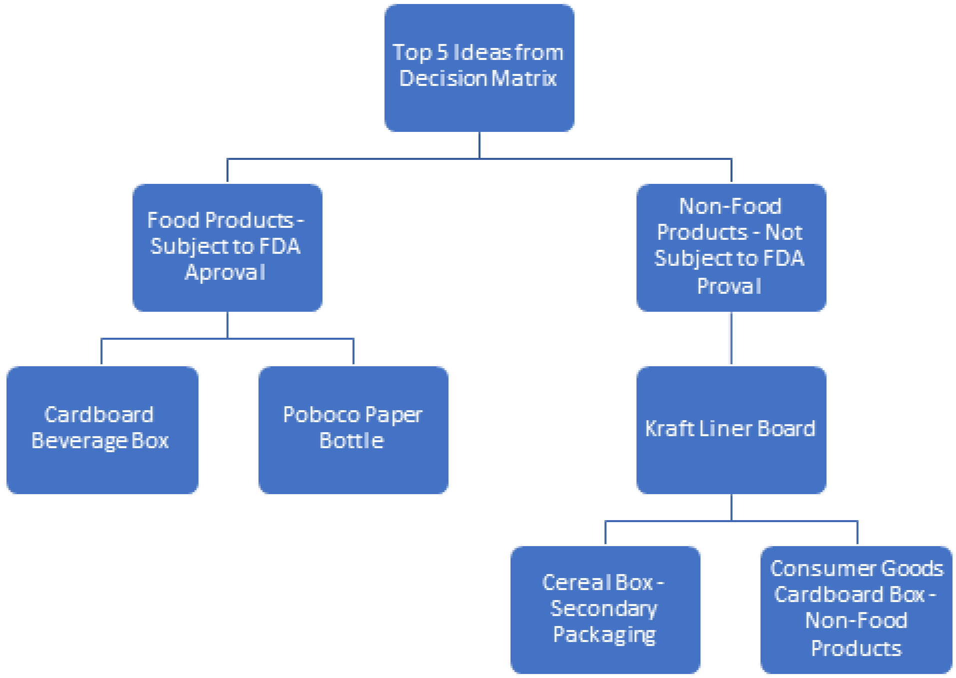


Figure 7: Secondary Concept Classification Tree bifurcated by regulatory areas that were informed by stakeholder and expert interviews

Prototyping

Raw Materials

To fabricate the samples three different types of fibers were needed. Sources of Old Corrugated Cardboard (OCC) fiber were obtained by purchasing standard single walled cardboard boxes (dimensions W x H x L - 12"x 20" x 12") manufactured by International Paper (IP). Kraft fiber was obtained by purchasing rolls of Natural Kraft Paper Roll fiber sold at Michael's Craft Store and manufactured by Creatology™. BNC fiber sources were derived from Kombucha fermentations conducted by Kombucha Biomaterials LLC. BNC fiber was previously pulped and dried into a shelf stable state prior to rehydration and disintegration for sheet manufacturing. All sources of paper pulps were shelf stable, processed, and dried forms of sheets and packaging board prior to material preparation.

Stock Mixture Concentrations

Each stock pulp mixture concentration was calculated to determine dry fiber per volume of pulp. Based on literature, a density of 1.5 g/cm^3 for plant-based cellulose was used to estimate volume contributed by OCC and Kraft fibers to the respective stock solutions (Sun, 2016. Similarly, 1.25 g/cm^3 was used for BNC to estimate density (Deepak et al, 2019). For

OCC fiber the total volume including fiber content was 37.95 L with a cumulative fiber concentration of 19.5 g/L. The Kraft stock solution contained a total volume of 24.36 L with a cumulative fiber concentration of 18.06 g/L. The BNC stock solution contained a total volume of 1.02 L with a cumulative concentration of 15.47 g/L of fiber. These calculations and concentrations can be seen in *Table 1*.

	BNC Stock	Kraft Stock	OCC Stock
Dry Fiber (g)	15.84	440	740
Water (L)	1	23.7	36.84
Total Vol (L)	1.02	24.36	37.95
Conc (g/L)	15.53	18.06	19.5

Table 1: Displays the dry fiber concentrations in each stock solution for BNC, Kraft, and OCC fibers.

Material Preparation

Old Corrugated Cardboard (OCC)

740 dry grams of single walled cardboard boxes were weighed and prepared by soaking in deionized water. After soaking for 20 minutes, the corrugated sheets were separated into the component sheets and shredded into roughly 8 cm by 10 cm pieces by hand. Hand shredded pieces were loaded into a 90 L Hollander Beater. This machine, pictured in *Figure 8,* is a stainless-steel basin and stainless-steel turbine specializing in paper fiber production by gently macerating fiber to retain original fiber lengths and characteristics. A gated gauge determines the clearance of paper fiber proximity to the turbine with smaller distances creating lower flow with higher fiber maceration, freeness, and delamination. The hand shredded cardboard was introduced into the Hollander beater in addition to 37.8 L of deionized water. At the tightest gauge length and clearance, the cardboard pieces were run through the Hollander beater until all observable fragments had dissipated into a slurry. The total run time was two hours until the fiber was freely disintegrated into the pulp mixture.

Kraft Fibers

480 dry grams of Kraft paper was weighed out and prepared by soaking in deionized water. After 20 minutes, the kraft paper fiber was hand shredded similarly to the single walled cardboard sheets. The Kraft paper was added to the Hollander Beater in addition to 23.7 L of deionized water. With the tightest gauge length and clearance, the Kraft paper had a total run time of 1 hour until the slurry was a freely disintegrated pulp mixture. Differences between the run time for the OCC and Kraft fiber can be attributed to differences in dry fiber, water volume added, and thickness or size of shredded sheets. Consistency was maintained with gauge length to produce similarly free pulps.

Kombucha Fiber

15.8 dry grams of Kombucha derived BNC paper was weighed out and added to 1 L of deionized water. Prior to the water addition, BNC paper was shredded by hand to facilitate a faster pulping time. These sheets were so thin and there was much less material compared to the other papers thus no soaking was necessary prior to pulping. Due to the smaller volume, an Oyster Pro 1200 hand blender was used to macerate the BNC pulp. This maceration process employs a more direct maceration mechanism than the Hollander Beater and might have impacted fiber characteristics. The BNC pulp was blended at high for five minutes until an evenly dispersed, disintegrated pulp was achieved.

Figure 8: Shows the Hollander beater. The right side houses the maceration mechanism operated by a belt driven turbine. Bottom right of the picture shows the lever that controls the gauge length. The left half of the Hollander beater is open face allowing for pulp consistency to be monitored while pulping is in progress.

Fiber Content and Blends for Sheet Types

The experimental design was set up to include two absolute controls with one set of sheets each consisting of 100% OCC fiber and 100% Kraft fiber. Based on literary sources it is expected that 100% OCC fiber sheet would exhibit the lowest tensile strength due to the shorter fiber length which results in lower fiber quality (Reichert, 1995). Contrasting, the 100% Kraft fiber sheet is expected to exhibit the highest tensile strength due to the higher fiber quality from longer fiber length and material purity. These sheet types serve as standard controls to compare our sheet formation process with standard laboratory and manufacturing sheet formation methods, with a satisfactory result mirroring industry notion about fibers types and sheet quality.

From these controls a series of sheets with blended ratios of Kraft and OCC fiber were formed with dry weight percentage ratios of 50-50, 40-60, 30-70, 20-80 (Kraft-OCC). These sheet blends were selected in relation to current industry practices for blending post-consumer waste and virgin fiber to optimize mechanical performance with costs and ecological impact. Typical industry practices indicate fiber blends of 50-50 up to 60-40 (virgin fiber-post consumer waste fiber) with upper limitations on OCC fiber addition due to poor mechanical performance. Thus, the four blended sheet types were selected with 10% increment additions of OCC fiber to exhibit discernable tensile strength differences and to compare with similarly formed sheets that included a BNC additive.

Four other sample sheet types were formed that included a 2% dry weight addition of BNC. 2% BNC addition was selected based on literature empirically demonstrating minor amounts of MFC (1-5%) can drastically increase tensile strength (20-60%) (source). These sheet blends mirrored the previous non-BNC sheets with dry fiber weight ratios of 48-50, 38-60, 28-70, 18-80 (Kraft-OCC) and serve to be compared in tensile performance with the non-BNC additive sheets. The small 2% kraft fiber difference between analogous sets of BNC and non-BNC sheets were intentionally kept small to ensure that kraft ratios were similar and with negligible difference. Paper thickness is generally measured and referred to in grams per square meter (GSM). A sheet GSM goal of 120 was attempted to be adhered to in accordance with typical standard GSM values for outer liner boards used for corrugated paper packaging.

Sheet Making

Lab Sheets vs Fourdrinier Sheets

Paper made at an industrial level is done on various types of fourdrinier machines where two parallel sheet formation fabric, known as a wire, are placed under tension while a slurry of paper fiber is injected in between the wires and ran through a combined series of heated rollers. This manufacturing technique creates artifacts in the paper formations such as anisotropic sheet formation. Here the cross direction, the dimension perpendicular to continuous sheet formation direction, exhibits different tensile strengths than the machine direction which is in line with sheet formation. These differences in sheet formation are notable and important when testing physical properties of fourdrinier machine produced paper.

Due to the extremely large production volumes of fourdrinier paper manufacturing, most experimental sheets are produced using laboratory scale sheet formation techniques. Formation of hand sheets for physical tests of pulp follows TAPPI standards T 205 (TAPPI, 2006). This protocol describes the detailed methodology to create the lab hand sheets and includes equipment such as a standard disintegrator and standard 159-mm sheet former with stirrer. The protocol also notes that using other types of sheet formers are not comparable and may yield different results.

Sheet Formation Chambers (SFCs) & Fourdrinier Fabric

A standard 159-mm sheet former is a cylindrical apparatus with a metal wire similar to the fourdrinier machine and a valve below. After agitation with the stirrer, the homogeneously dispersed pulp slurry in the cylinder is drained forming the sheet on the wire. Based on unavailability of equipment described in TAPPI T 205 measures were undertaken to form sheets as close to TAPPI guidelines as possible with equipment made by hand (TAPPI, 2006a). A rectangular sheet formation chamber (SFC) was formed using 1.27 cm thick plexiglass sheets with dimensions (L x W x H) of 60.96 x 50.8 x 15.24 cm. Two horizontal faces (with respect to length and width) of the SFC are sunk into the interior of the rectangular prism and form a sheet formation layer on the top and liquid column support layer below, acting akin to the wire layer and the valve in the standard sheet former. The sheet formation layer is non flexible and with regular 1.9 cm square holes removed from the bed with 0.635 cm intervals in between. The end result is a supportive layer with a 55.88 cm to 45.72 cm sheet formation area that a fabric can be applied on top allowing for passage of fluid and capture of fibers; a full representation of the SFC can be seen in *Figure 9*. All plexiglass was cut using an Orion 600 W laser cutter and was sealed using 2-part JB Weld industrial watertight adhesive. It is acknowledged that rectangular SFC differs from the circular sheet former recommended by the protocol and may exhibit less even drainage which can adversely affect sheet formation. However, test sheets produced appeared to have even and satisfactory fiber distribution upon visual inspection.

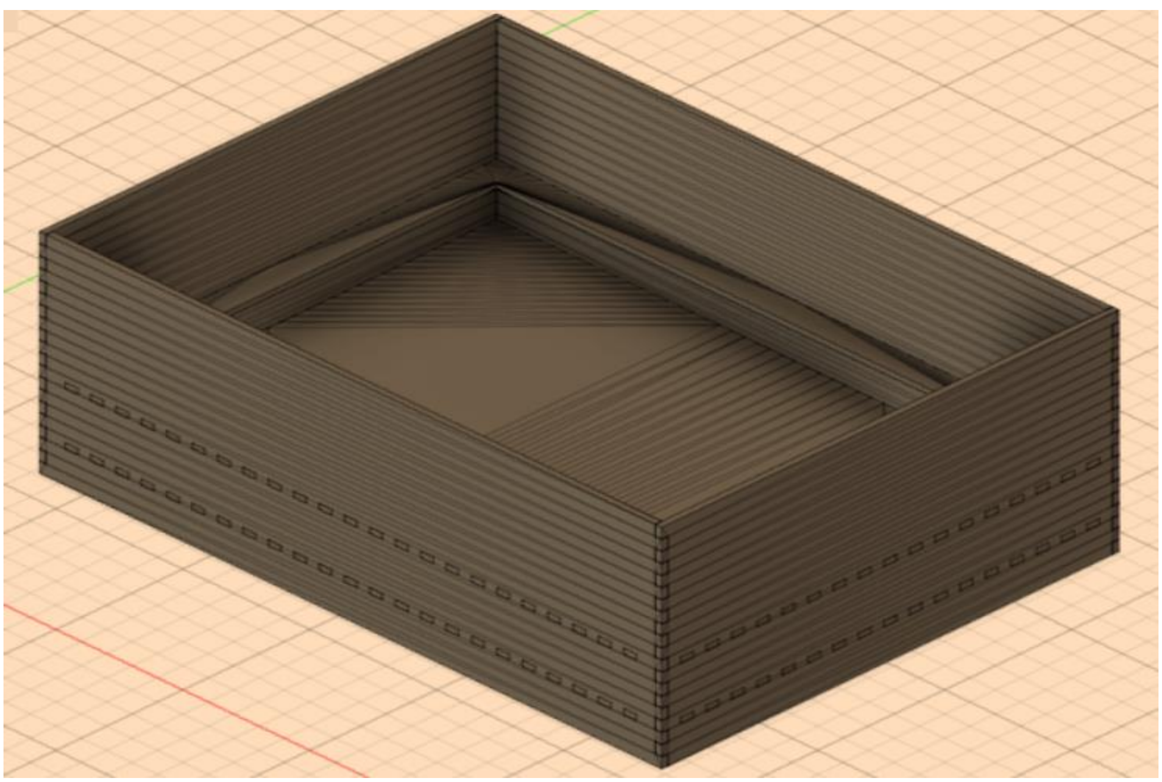


Figure 9: CAD model used to cut plexiglass sheets for Sheet Formation Chamber (SFC) (Dimensions:17.5 x 24 x 10in^3). The edge of the sheet formation layer can be observed abutting from the interior. The small rectangles on the perimeter of the exterior further indicate where the sheet formation layer and the bottom layer that supports the water weight are in relation to the height of the SFC.

Without the metal wire available that was recommended by TAPPI T 205, fourdrinier wire was obtained from Asten Johnson, a paper manufacturing operation supplier. Metal surface wire noted by TAPPI T 205 has a wire diameter of 0.067-0.071 mm with a density of 60 threads per cm. The forming fabric from Asten Johnson is a polyester fiber and possesses a 0.11 mm thread diameter with a 39 threads per cm weave density.

Figure 10: 6 SFCs and recyclable drainage systems set up in parallel pre and post staging with water and border-weighted fourdrinier catching/drying stage.

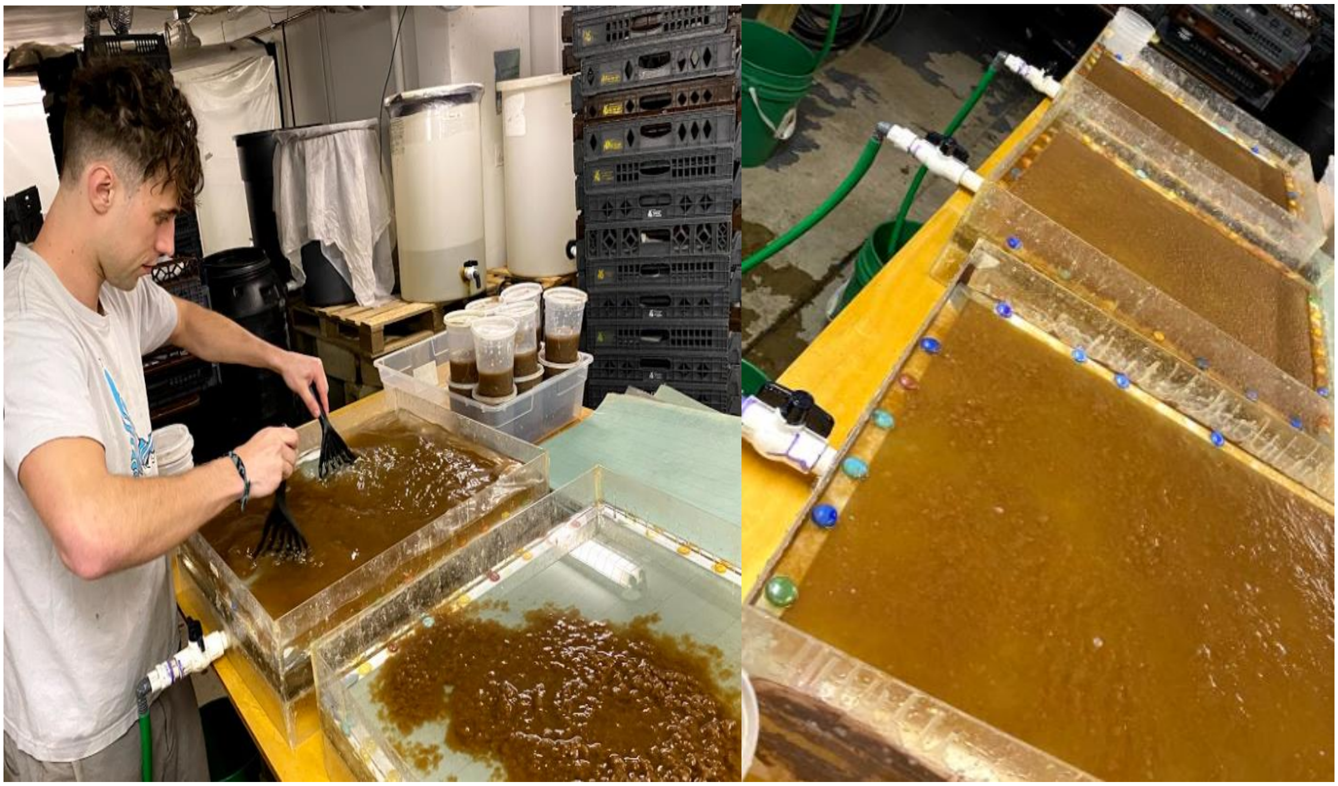


Figure 11: Pre-drainage A. homogenization of the various grades of Kraft, OCC and BNC fiber
Post-drainage B. sheets formed via the drainage and filtration of the homogenized water/fiber bath.

Figure 12: Sheets formed on fourdrinier fabric were removed from the SFCs and arranged in a highly ventilated stack for proper drying.

Process of Sheet Formation

Abiding by as much of the TAPPI T 205 protocol as feasible, Sheet Formation Chambers (SFCs) were filled with 15 L of deionized water. Following, forming wire from Asten Johnson was dipped in a 10% ethanol solution to remove any air bubbles (that would disrupt sheet formation). The sheets were then placed on top of the supporting plexiglass formation layer after which a 5 cm thick weighted frame was placed on top of the fabric to prevent flow around the perimeter of the SFC. After ensuring flat and even coverage of the weighted frame across the fabric, pulp mixtures specific to each sheet type were poured into the basin of the SFC seen in *Figure 10*.

Vigorous agitation by hand instruments was completed for 3 minutes to ensure even pulp distribution and mixing which is depicted in *Figure 11*. Once no color distinctions between pulp type or density were discernible visually, the valve was opened then draining water from the centrally located port at the bottom of the water column. 3 sheets of each 10 different sample types were produced creating 30 sheets in total to allow for ample sample selection in case poor fiber formation resulted in substandard sheet formation.

Following complete drainage of the SFC basin, the weighted frame was carefully removed to ensure no water droplets disrupted the cellulosic web formed on top of the fabric. From there the fabric was placed onto a drying rack overnight, see *Figure 12*. The SFC process was reset and repeated until all 30 sheets were formed. Once the sample sheets had been dried, a knife tip was inserted under one of the corners of each sheet and was used to peel the sheet free from the forming fabric. Due to the high GSM of the sheets, integrity of the sheet was maintained throughout the peeling process and no disturbance or defects were observed during the removal process.

TAPPI standards also include a weighted drying and “couching” step where another type of paper or fabric is placed atop the wet sheet and excess moisture is pressed out while compacting the cellulosic web. This step adds enhanced strength to the dry sheet; however, due to material constraints double layered couching was not possible and sample sheets formed were dried with an open-air face. This factor and the lack of compacting fibers from additional force application likely weakened the end sheets tensile strength compared to sheets where protocol was directly adhered to.

Sample Cutting

In accordance with TAPPI T 494 sheets were cut to 25.4 mm by 203.2 mm using hydraulic cutters from UVA Printing (TAPPI, 2006b). The hydraulic cutter ensured straight, even, and precise cuts within the tolerance listed by the protocol. This critical step allowed for the most accurate tensile test outcomes because small deviations or jagged edges for the specimen will multiply force rendering lower maximum tensile strengths. A representation of the final samples can be seen in *Figure 13.*

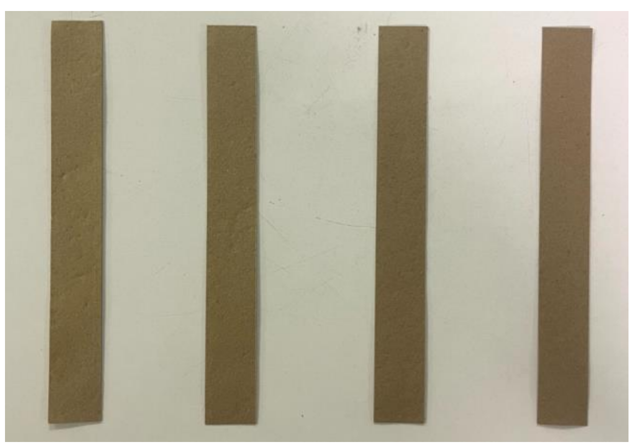


Figure 13: Displays the final paper sample strips (25.4 mm by 203.2 mm) used for tensile testing with the Instron according to TAPPI T 494 protocol.

Testing

Tensile Testing

Figure 14: Displays an Instron used for paper sample tensile and strength testing. (Instron, 2020)

In accordance with TAPPI T 494 10 samples of each fiber blend type were tested using an Instron 5543 with a max load capacity of 500 N located in the BME IDEAS lab in Thornton. As prescribed by the testing method, two-line clamp jaws were fixed 177.8 mm apart, and a strain loading rate of 25 mm per min was programmed into the method using Bluehill 2 software.

Samples were evenly clamped in place and parallel to the direction of motion. The force meter was zeroed prior to each test and did not have any tension applied to the sample before test initiation. Each sample was weighed, recorded, and used to calculate GSM prior to testing. Sample thickness was measured and used to determine volume through which the Instron applied force. This testing method was run for 10 specimens for all 10 types of unique fiber blends until failure without slippage or rejected samples. Continuous raw data for force applied, strain, and time were recorded and uploaded into CSV Excel files. Maximum tensile strength was calculated as the highest force applied over the sample width before specimen failure; failure being defined as 40% reduction in the maximum force applied.

Results

Paper Thickness - Average GSM and Range

Effectivity and precision of the SFC as well as the quality of fiber dispersion and drainage can be described by average and standard deviation of the GSM of the samples. As seen in *Figure 15,* the average GSM for all samples tested 112.743 with a standard deviation of 15.63. These values indicate that fiber was lost during the sheet formation process. This is likely attributable to fibers escaping around the perimeter of the forming sheet and weighted frame. The wide standard deviation indicates that sheet consistency and weight throughout the formation process varied greatly. Paper thickness and GSM greatly impact associated mechanical properties like tensile strength; thus, varying GSM is not ideal indicating fiber type impact. However, in analyzing tensile maximum results GSM was accounted for and normalized linearly following the Tensile Index protocol described by TAPPI T 494. Initial average results of tensile force display 100% Kraft samples with the highest average at 33 +/- 7.5 N and 100% OCC samples with the lowest average at 9.8 +/- 3.1 N This direct comparison is further substantiated by the GSM for both of these sample sets averaging nearly the same at ~106 GSM. These results aligned with industry knowledge of Kraft and OCC fiber quality and presented a positive outlook for qualitative comparisons of the improvised sheet formation and fiber sourcing to the literature.

	100% Kraft		50% Kraft		40% Kraft		30% Kraft		20% Kraft		0% Kraft	
	GSM (g/m^2)	Tensile (N)	GSM (g/m^2)	Tensile (N)	GSM (g/m^2)	Tensile (N)	GSM (g/m^2)	Tensile (N)	GSM (g/m^2)	Tensile (N)	GSM (g/m^2)	Tensile (N)
AVG	106.56271	33.013	113.343977	27.382	110.631471	25.197	125.937752	24.098	102.68771	19.009	106.75646	9.84
STD	11.660848	7.48912	14.2156989	5.7530066	16.2475871	3.30410536	12.7542119	4.05737134	11.223409	2.8736019	14.683331	3.14094112
w/ 2% BC			48% Kraft		38% Kraft		28% Kraft		18% Kraft			
			GSM (g/m^2)	Tensile (N)	GSM (g/m^2)	Tensile (N)	GSM (g/m^2)	Tensile (N)	GSM (g/m^2)	Tensile (N)		
AVG			117.606485	34.52	125.937752	33.505	117.412735	29.249	100.55645	21.814		
STD			14.5578058	6.932532	11.1488342	9.5336215	15.0688595	8.39438099	14.683331	4.683131		

Average GSM = 112.743 +/- 15.6308

Figure 15: Matrix of average GSM and average maximum tensile force before failure in Newtons of sheets of varying composition, both with and without the addition of BNC.

Raw Bluehill-Instron Data

As seen in *Figure 16,* a sample of the raw specimen data for load over extension of the 50% Kraft fiber sheets is shown. Each of the 10 trials was offset by 1 mm when plotting the graph to better discern tests from one another. All curves follow a consistent pattern for force and deformation response. None of the samples tested experienced slippage or other improper failure while undergoing tensile loading.

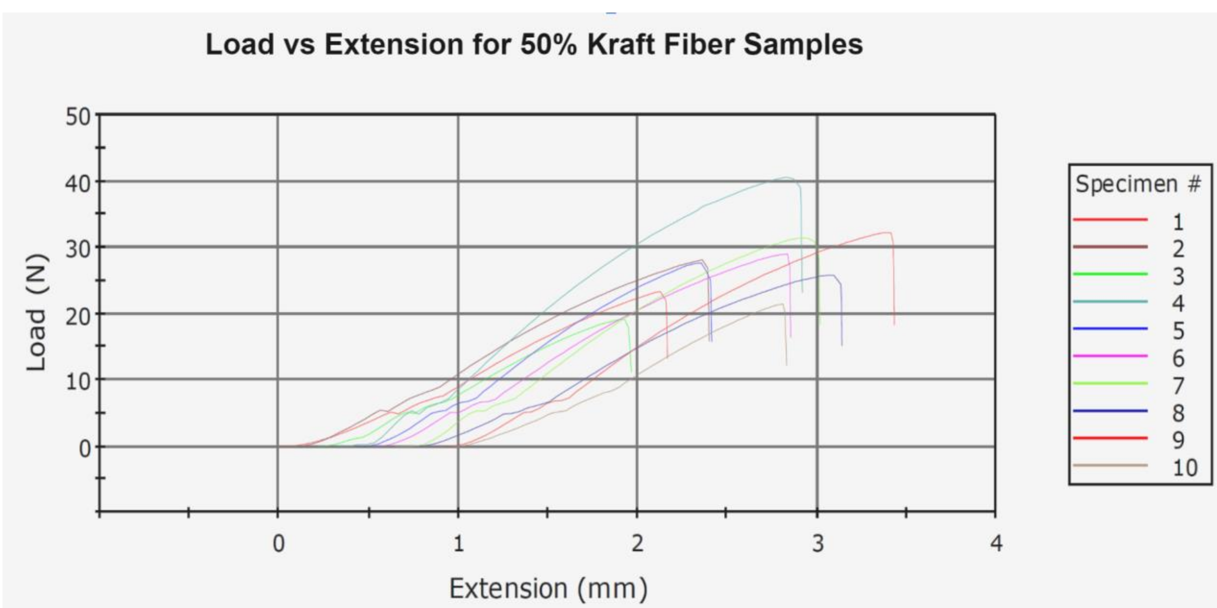


Figure 16: displays the load vs extension performance for all 10 non-BNC 50% Kraft 50% OCC paper samples. A recurring stress strain curve can be seen among all of the samples exhibiting consistent plastic deformation followed by abrupt failure.

Tensile Index - Controlling for GSM

Analysis was conducted on the raw data and averages to control for GSM variation. As seen in *Figure 17*, the tensile index for paper is calculated by dividing the average maximum tensile force by the specimen width (2.54 cm) and then dividing by the average GSM. This manipulation assumes a linear correlation between GSM and tensile force and is regularly used by the paper industry. The horizontal axis is demarcated by the percentage dry weight of kraft fiber in each of the sheets. Two separate groups of data are apparent and represent the tensile indexes of vs kraft fiber percentage for samples with and without the two percent BNC addition. Plotting a second order polynomial regression for each data set displays a 0.98 R-squared value for each data set indicating a tight fit between the regression and the empirical data. The polynomial regression for each data set obtained a higher R-squared than linear regressions. This implied non-linear relationship is congruent with literary findings that indicate improved fiber quality furnish can improve tensile strength up to a point before other formation factors have greater impact on mechanical integrity (Johansson, 2015). Noticeably, the BNC additive curve is always above the non-BNC additive curve which suggests that the addition of BNC fiber contributes to an increased tensile strength even while linearly controlling for GSM through tensile indexing. This data analysis provides a basis to substantiate the technical claim and hypothesis that the addition of BNC can be used to substitute kraft fiber with OCC fiber. Additionally, similar horizontal axis values between the two regressions offer insight into the amount of Kraft fiber that can be reduced while maintaining performance. The average tensile index is 0.24 for the 50 percent kraft fiber sample, and the most similar BNC additive sample has a tensile index of 0.25 and contains 28 percent kraft fiber. Similarly, another horizontal grouping of non-BNC and BNC samples each shows a tensile index of 0.23 and 0.24 respectively. The kraft content for each sample set is 40 percent and 18 percent respectively. These results demonstrate that by using the manufacturing methods employed, the tensile index (and other correlated mechanical properties) can be enhanced with minor addition of BNC to substitute up to 20 percent dry weight kraft fiber with OCC fiber. Interestingly, the 100 percent kraft paper exhibits a similar tensile index at 0.31 to the tensile index of the 48 percent kraft paper that includes the BNC additive. This information suggests that fiber substitution could be higher with additional testing and experimental design. While drawing comparisons between BNC and non-BNC data sets is promising, standard deviations for each sample type are higher than desired for conclusive, definitive claim of the hypothesis. Relative errors ranged from 14.2%-30% and is likely the result of deviations and modifications made to the TAPPI testing and sample formation protocol that is explored in depth toward the future works section of the report.

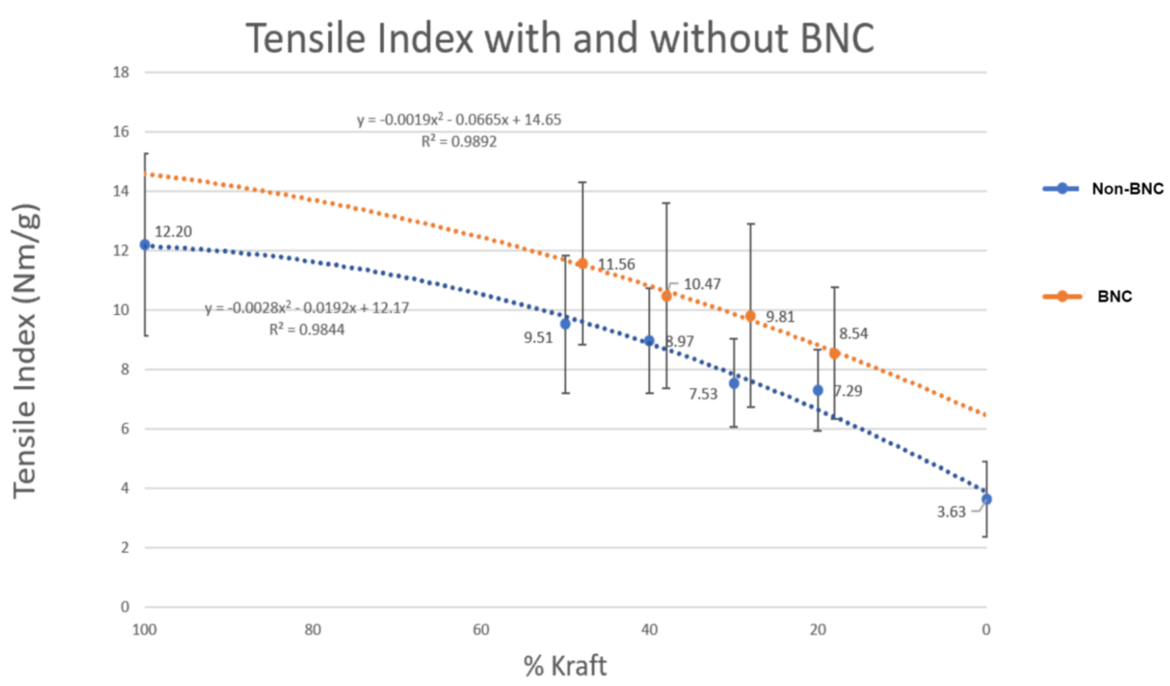


Figure 17: Average tensile index for 10 samples of both BNC-treated and untreated papers plotted according to decreasing Kraft fiber percentage

Using data from an ISO 14040 life cycle analysis that holistically compares the environmental impact of recycled fiber and Kraft fiber that is produced in Germany (Terlau, 2017). Emission analysis specifying greenhouse gas effect (kg CO_2 equivalence / ton) demonstrated that recycled fiber emits 34.1% as much kg CO_2 equivalence / ton as wood derived Kraft fiber which emits 351.7 kg CO_2 equivalence / ton. In terms of energy expenditure (kWh/ton), recycled fiber uses 24.9% of the kWh/ton when compared to the processing of Kraft pulp which totals 1,402.6 kWh/ton. Finally, water usage (Liter / ton) for recycled fiber is 28.1% of what is used for Kraft pulp which totals 32,000 Liters of water / ton. Consolidating these comparative data points, a series of equations was developed to quantify the environmental aspects of substituting a higher recycled fiber content with a lower Kraft fiber content in *Figure 9*. Looking at *Figure 18*, an increase in OCC fiber from 50-50% (Kraft-OCC) to 28-70% results in a 20.3% decrease in emissions, 24.9% decrease in water consumption, and a 23.2% reduction in energy expenditure (the other 2% would consist of BNC). These are the contextualized reductions and environmental sustainability that could be achieved with BNC additive implementation

These savings are significant and reserved only to the raw material processing for kraft and recycled paper fiber. These values do not include the expenditure of actual paper creation but only the impact of the feedstock material used in the paper manufacturing process. Importantly, the calculations do not include the emissions, energy expenditure, or water usage for processing BNC fiber since it has never been conducted at an industrial pilot scale. While these reductions are estimations; when considering the inherent purity of BNC cellulose and that most pollution, energy, and water consumption is used to purify plant matter into refined kraft cellulose our group uses these facts as justification for the light impact that BNC processing would have while conducting further analysis and exploration.

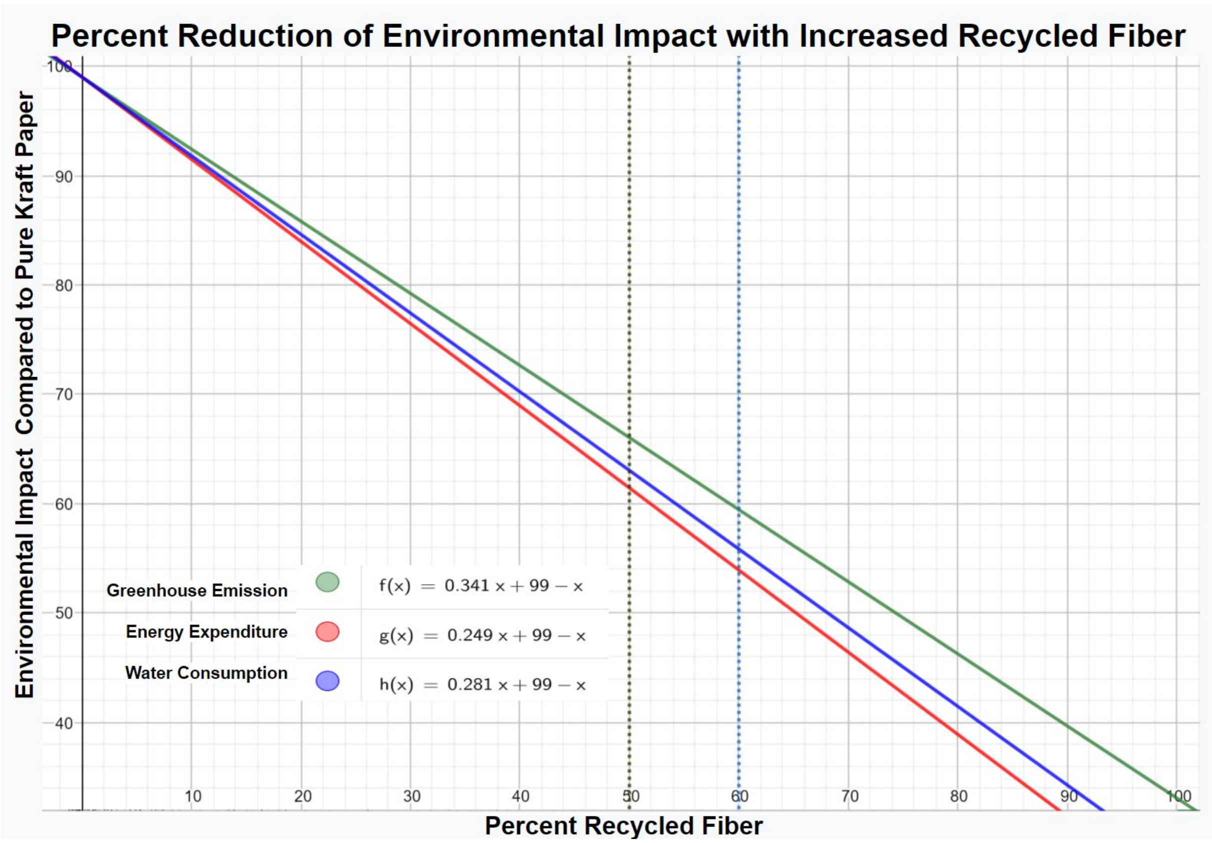


Figure 18: showing the reduction of greenhouse emission, energy expenditure, and water consumption based on the percentage increase of recycled fiber content per ton of paper. Y-intercept displays baseline environmental impact of a 100% Kraft pulp paper. Units for greenhouse emission are in Kg of CO_2 equivalence per ton, units for energy expenditure are in kWh per ton, units for water consumption are in liters per ton Vertical lines at 50% and 60% demonstrate visually the modest 10% increase in recycled fiber can have across these three LCA values. Note that 2% of the fiber is BNC and environmental impacts related to its processing are not shown.

Comparison in Relation to Industry Standards, Methodology, and Results

Raw Materials

OCC

Sourced from old cardboard and included slight amounts of ink and adhesive that may typically be removed during the fiber recovery process to create post-consumer waste fiber. These factors may have created lower quality fiber that while matching qualitative comparisons to industry knowledge was not representative of actual recovered fiber.

Kraft Fiber

Sourced from already formed and dried kraft paper sold at Michael's Craft. Repulping dried fiber is undesirable since previously dehydrated fiber suffers hornification or irreversible reduction in fiber size (source). This fact alongside the additional blending that would further shorten the fiber should be acknowledged in potentially reducing the quality of the kraft pulp produced. Ideally kraft pulp would be obtained directly from a pulp mill after processing

Hollander Beater

Both of these aforementioned fibers were prepared by the Hollander beater and while it is an explicitly specialty paper blender, it operates with a different mechanism than the disintegrator recommended by the TAPPI standards. Kombucha based BNC was also from previously dried fiber which may hold an impact, as well as the fact that a hand blender was used for preparation.

Finally, in terms of raw material preparation, no fiber analysis was conducted to determine the average fiber lengths, widths, or curl which would further indicate quality of each fiber type. This equipment was not available but should be considered in further experimentation to better elucidate structural and physical properties of the fibers and how that relates to sheet quality.

Sheet Formation Chambers (SFCs)

The SFCs also deviated from the prescribed TAPPI protocol for hand sheet production. The SFC constructed was rectangular instead of circular which may have created drainage irregularities leading to less uniformity in the cellulosic web. Additionally, the fabric used while coming directly from a paper manufacturing supplier was polyester instead of metal and had a thicker thread length and a resulting higher thread count. Also considering the wide variations in GSM from tested samples indicate that sheet formation quality could be more precise. Furthermore, the fact that the total average GSM for all samples was lower than 120 suggests that fiber loss during sheet formation was an attributable factor. Importantly, it was assumed that even with fiber loss that ratios of fiber types would remain the same; however, based on differences in fiber size and quality that assumption may not qualify and jeopardizes the integrity of the results that rely on accurate fiber content percentages.

Other deviations from TAPPI hand sheet formation protocol included not “couching” and laying a secondary fabric on top of the wet sheets. This added fabric and mechanical dewatering through force leads to fiber compression within the sheet which strengthens the resultant paper. Samples prepared for this experimentation did not undergo this process and as a result tensile forces before failure may be higher than what was measured in this report.

In industry practices, fourdrinier machines apply two fabrics to the paper and mechanical fiber compression as well. These and the other previously noted deviations from TAPPI standards limit the quantitative applicability of these results to industry standards and other market products. While results fell in line with expected outcomes based on literary research, the quantitative results apply most directly to the other samples or any paper produced using this outlined methodology. Qualitative trends demonstrated here are expected to be congruent results with more strict TAPPI standard adherence or in industrial scale implementation; however, the extent could be lesser or greater based on the above factors.

In contextualizing the sustainable benefits of increasing OCC fiber, it should be mentioned that those reductions in emissions, energy expenditure, and water usage do not include the processing of BNC fiber or the production of the paper itself. While these results are indicative of promising results, more research must be conducted to further define the sustainability of employing this fiber substitution.

Wettability Testing

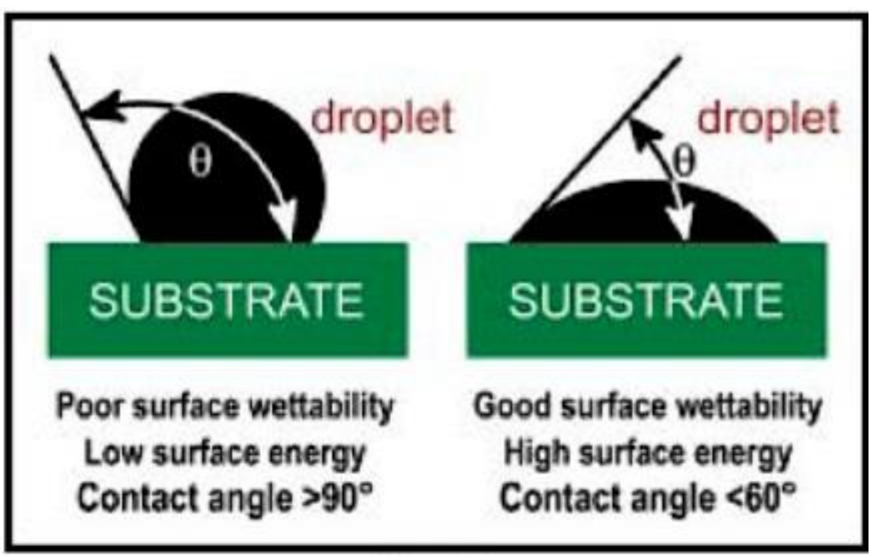


Figure 19: Visual definition of water droplet interaction between a hydrophobic or hydrophilic

substrate. (Adhesion Bonding, 2012)

For our product to be successful we determined that it must be able to exhibit hydrophobicity. This will allow our product to be able to withstand exposure to water whether that exposure be intentional or unintentional. Giving this hybrid biomaterial an increased resistance to water opens up more applications as well as increased durability. The BNC paper by itself offers almost immediate water droplet absorption with no visible droplet formation. When water is applied to uncoated BNC paper the water droplet immediately gets absorbed. Cellulose in itself is hydrophilic and absorbs water on contact. Kraft pulp, which consists mainly of cellulose, accordingly has a high affinity to water (Liukkonen 1997). To modify this material behavior our group hypothesizes that we can add a PHB coating the BNC sheets and increase the hydrophobic properties of the material. This coating will also add strength and durability to the BNC paper all without diminishing its biodegradable properties. The wettability testing described below was derived from TAPPI T 458 - Surface Wettability of Paper to the best of our ability with an example methodological diagram shown in *Figure 19*. This TAPPI standard provides a method for calculating the contact angle between air and liquid on a paper surface. The contact angle provides a metric for determining the resistance of a surface to wetting by a liquid.

Preparation

To test wettability angle, the BNC sheets were first coated in PHB. During our initial experimentation we discovered that the most effective way to coat the BNC sheets was with a household iron. The preliminary modifications needed before the wettability testing require the team to coat six samples in PHB. Three of the samples would be tested on the wire side of the paper and three on the air-dried side. The wire side of paper is the side of the paper that dries facing down on the fourdrinier wire and the air-dried side is the reverse. The BNC strips were first trimmed down to 4 inches in length and labeled according to the side that would be coated, either wire or air-dried. Next, 15 grams of PHB pellets were placed on a parchment lined baking sheet and covered with another sheet of parchment paper. The iron, at 350 degrees, was then placed on top of the parchment paper and left to sit for ~10 minutes. During this time the iron was moved around the parchment sheet to create even heating and melting. The top parchment paper was then removed and the six sampled placed onto the molten PHB with the correct side face down. The top parchment was then replaced and the iron pressed down to adhere the PHB to the BNC samples. The complex was allowed to cool then the samples cut out with scissors. The samples were also weighed before and after the coating in order to find the amount of PHB on each sample. This can be used to roughly indicate the thickness of the PHB coating on the BNC sheet.

Procedure and Data Collection

After the six samples were coated the wettability testing could begin. The procedure begins with taping one strip, coated felt side up, to a level, horizontal table. This secures the specimen to the table to prevent distortion during wetting. Next a micropipette was set 3 cm above the specimen and used to place a 10 uL drop of DI water onto the surface of the paper. After 5 seconds, a picture was taken using an iPhone from 5 cm away. After 60 seconds, a second picture was taken. This process was repeated on the other two felt side samples. Then three more tests were performed but this time using the air-dried side.

$$R = \frac{C - C'}{(t_2 - t_1)}$$

Equation 1: Angle of wetting calculated from the change in wettability measured at t_5 and t_{60}

After the pictures were taken, they were uploaded into ImageJ in order to find the contact angle. The contact angle is represented by the letter C in *Figure 20.* First a line was drawn tangent to the part of the droplet that came in contact with the specimen. Next a second line was drawn along the base of the sheet. The angle tool in ImageJ was used to find the wettability angle. This was repeated for all specimens and at both time intervals. *Equation 1* gives the equation for finding the rate of wettability angle change. With the wettability angle being defined as C at 5s. C' denotes the contact angle at the 60s mark. The variables t_1 and t_2 denote the time at 5s and 60s respectively. Once both contact angles were recorded for one sample the rate at which the angle of wetting changes (R) could be calculated using *Equation 1*. A complete wettability analysis of a droplet can be seen in *Figure 21.*

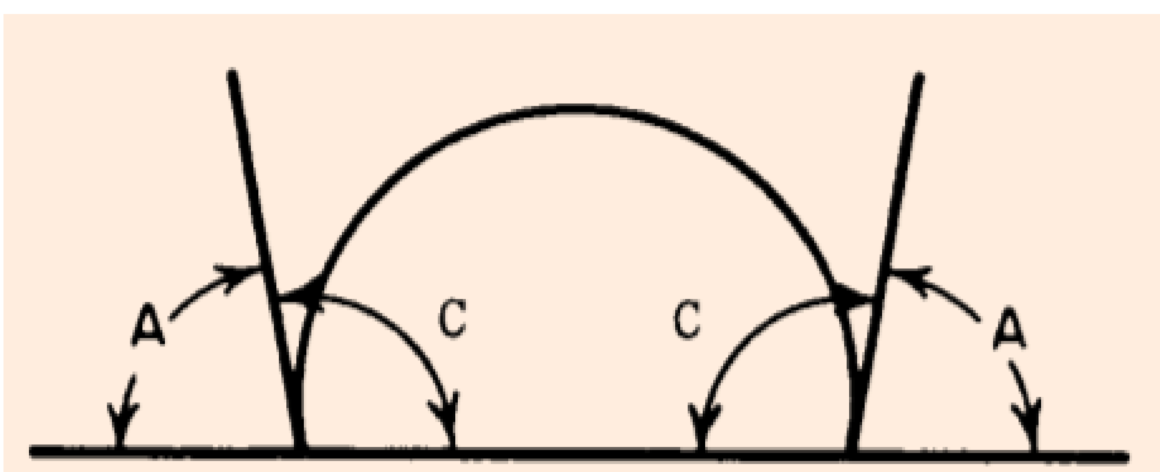


Figure 20: Diagram of proper Wettability Angle measurements

Wettability Data Analysis

After wettability angle analysis was completed, the relevant data was recorded in *Figure 22.* This information will be helpful as it will allow our group to compare the wettability of our hybrid material to other industry standards. For example, good writing paper has a wettability angle between 90 and 110 degrees. Outside of these angles feathering or breaking could occur. The TAPPI T 458 - Surface Wettability of Paper definition for hydrophobicity is a wetting angle of 90 or greater. Looking at the data all of our wettability angles are greater than 90 degrees. The average wettability angle for the experiment was 108.33 +/- 5.28 degrees. The rate of wettability angle change was also within acceptable levels for hydrophobic materials. This data allows us to confirm our hypothesis that PHB would increase the hydrophobicity of the BNC sheets. Therefore, the hybrid material is more water resistance and meets the requirements set forth last semester. Chiefly metrics pertaining to shelf life, durability and inkability.

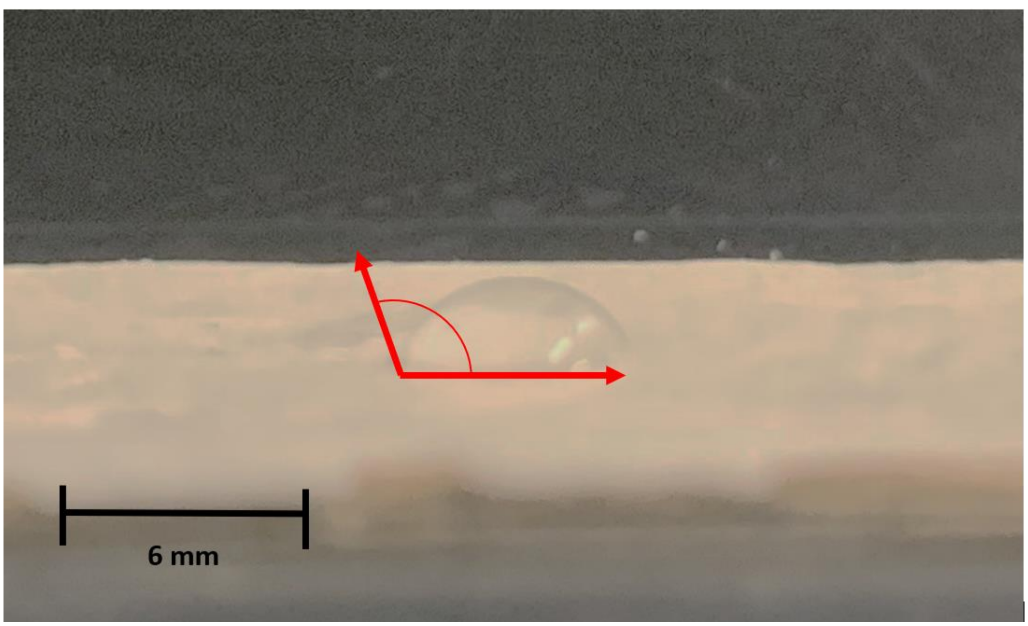


Figure 21: Wettability angle test performed on PHB coated BNC paper

		Amount of PHB on Paper (g)	Wettability Angle at 5s (C, degrees)	Rate of Wettability Angle Change (R, degrees/sec)
Felt	1	1.06	112	0.07
	2	0.96	103	0.15
	3	1.14	105	0.09
Air Dried	4	0.97	108	0.16
	5	0.85	117	0.13
	6	0.99	105	0.09

Figure 22: Matrix of the Amount of PHB on BNC samples, Wettability Angle, and Rate of Wettability Angle Change

Design in Detail

The success of the hypotheses showcase that we have created a product that can act as traditional paper packaging but with increased strength, water-resistance, and increased recycled material. The final design we have arrived upon assumes this product is intended for secondary (non-food contact) packaging. Our composite material exhibits the important properties that would be needed to mimic current products on the market. This project showcased the ability of a BNC addition to a Kraft/OCC mix to increase tensile strength or alternatively increase recycled fiber content while maintaining mechanical performance. The mechanical properties matrix highlighted burst strength as the most important mechanical property when developing this material because burst strength dictates the ability of a material to hold what is inside. However, direct testing of burst strength was unavailable and increase in tensile strength typically correlates with increased burst strength. For the wettability testing, we were able to demonstrate that the PHB coat increased the water resistance of the BNC uncoated material. This increase in hydrophobic properties also showcases progress towards the shelf-life metric that prevents water absorption during package transit. Printing and inking properties are also optimal at specific wettability angles. This metric is relevant to any design or labeling that would go on this packaging. With these properties in mind secondary non-food packaging applications are the final design. Examples of secondary packaging include the boxes they use to enclose individually wrapped items such as utensils, clothing and household cleaning items. Secondary packaging might include brand emblems, product specifications, instruction and designs. The goal of secondary packaging is to keep product contents together, defend against damage and bundle items so that they are visually appealing. The increase in burst strength and hydrophobicity helps with these goals. Increased inkability allows for designs and text to be clearly put on the box. Our ideal packaging would be a semi-rigid liner board used to package consumer goods that if uncoated can re-enter the raw material loop through recycling or if coated in PHB can be disposed of without shedding inert petroplastics into the environment.

Given the unique manufacturing methods employed, direct industry comparisons to the performance of market available secondary packaging do not surpass the threshold for immediate design deployment. However, qualitative performance and internal comparisons among samples indicate paper pulp blends including small percentages of BNC additive can perform at much higher tensile strengths while increasing post-consumer fiber content (OCC) in the fiber furnish. The same notion applies for PHB coatings in that application technique were less precise and incongruent with current manufacturing practices for direct comparison but internal comparison amongst the experiment yielded promising results for increasing hydrophobicity in BNC infused paper.

Future Direction and Considerations

Now that we have quantified the strength contributed by the addition of kombucha derived BNC fibers and demonstrated increased hydrophobicity with PHB coatings for samples formed using our unique methodological process, next steps proceed with the recreation of all experiments using industrial standards of manufacturing to compare to initial results elucidated above. For direct industry comparisons and determinant successes Test Liner for boxes at 186 GSM should achieve a burst strength of 250-475 KPa and at 107 GSM should exhibit a tensile strength of 5.6 kN/m while using lower kraft fiber concentrations that market available controls (Goyal, n.d.).

Specific to coatings, the exploration of various instances of industrial manufacturing PHB coatings such as extrusion coatings is necessary. This experimentation will explore various methods of using the materials in conjunction, most often through coating and advanced blending techniques (not currently accessible). PHB offers to enhance the durability and several barrier properties of paper products and is a significant improvement on the use of petroleum based labels, coatings and other use cases. One of the future avenues of this project would be exploration into a wider variety of market applications. Barriers such as price and volume of units provide obstacles to the implementation of a project like transcending from lab bench stage to industrial manufacturing integration. Next steps would also include working to perform and achieve standards properly, including TAPPI, ASTM, ISO, ISTA, etc. standards and subsequent certifications to develop a specific packaging application of our materials.

Reflections on the Design Thinking Process

Assessment of Design Viability

Reflecting back on the design processes, prototyping and testing we feel that our biomaterial additives provide a more sustainable option for paper packaging while maintaining product performance standards. While still in nascent development, our team was able to put forth two key metrics and test them with industry standards in mind. The team used TAPPI standards to ensure that our testing was sufficient to be presented to stakeholders. Our two hypotheses focused on proving that our material can perform at levels similar to counterparts in the market. The tensile testing showed that the addition of BNC to a Kraft/OCC paper can increase the tensile strength with lower levels of Kraft fibers increasing the overall proportion of recycled fiber. In order to increase the functional applicability and market for the liner board, the hybrid material would have to exhibit hydrophobicity, a property that our BNC paper doesn't inherently have. Our second hypothesis and testing showcased that the addition of PHB to the paper was able to make the hybrid material hydrophobic. This is supported by the average wetting angle averaging over 90 degrees. Our mission was to attempt to create a material that was able to be successful in meeting the “triple bottom line” and achieve industrial ecology. In our testing we were successfully able to hybridize two materials that exhibit these characteristics.

Individual Reflections / Contributions

Alec Brewer

My role served primarily to provide both technical and commercial background to the scope of our work, as well as to provide plastic-specific insights regarding the design and implementation of our conjunctive biomaterial use. My background in the biomaterials space is derived primarily from the countless market discovery interviews and regulatory dives I’ve performed in the last year in the development of my own venture, Transfoam LLC. My inquisitive nature coupled with my academic training in bioengineering (IDEAS, GenMod, Biomanufacturing, D&D, etc.) and (social) entrepreneurship (STS 4580, Social ENTP, STS 45-4600) have prepared me for successful execution of our thesis portfolio and responsible innovation in the biomaterials and broader sustainability space in my path beyond the University. In light of this project, I plan on exploring novel, high-tech blending methods to create unique PHB/BNC paper blends alongside our portfolio of tempered PHB. Targeting consumer packaging, ag and medical markets provide a strong case of the use of these materials both in conjunction and in isolation on the forefront of the ongoing sustainable transition.

Cutter Grathwohl

The idea for working with Kombucha derived BNC was derived from my last four years of research and development of alternative non-plant based cellulose additives through my venture, Kombucha Biomaterials LLC. Personally, the aim for this project was to demonstrate the high-level impacts that the addition of minor amounts of BNC can have on mechanical performance and environmental impact of paper packaging. Considering limited accessibility to university resources due to the pandemic, I am proud of the physical material products and tests conducted. In a year when so much of life went online, this project reminds me that fundamentally we live in a physical, material world, and my belief is that biomaterials will provide the technical solution for packaging sustainability issues. Looking forward, the continued development of IP to leverage existing waste products to reintegrate into raw material resource loops and improve product functionality and end of life comes next!

For the successful completion of this project an experimental design that constrained and directed a multitude of varying factors and controllable variables was required. The knowledge to produce this experimental design as well as research and recreate standard experimental protocol was derived from my experiences in the Biomedical engineering curriculum. Additionally, data manipulation such as standardization and normalization were necessary and accessible through my lab experience at The University of Virginia. For more definitive results, more strict consideration should be made to raw material sourcing as well as closer adherence to TAPPI standards through proper equipment. These adjustments should reduce error from paper sample testing. Additionally, the extension of material testing properties could include smoothness and the other highly specific but unavailable tests that were identified as important for paper packaging.

Ryan Crosser

For the duration of this project, I leaned on my past experiences from my Biomedical Engineering (BME) minor and Material Science Engineering (MSE) class experiences for the scope of materials, testing, testing procedure, and data analysis. For the business case and business plan development, along with conducting industry conversations with subject matter experts, I drew upon my Entrepreneurship minor and class experience within the McIntire school of Commerce.

Based on where the project currently stands, I would recommend continuation of research into product applications, specifically within up-and-coming markets. Cannabis currently serves as the rapid growth market that contains potential product applications, but as regulations increase and public sentiment for more circularity rises there will continue to be a demand for greener and more circular packaging options across all products and industries.

Wyatt Black

I chiefly drew upon skills I learned in the BME curriculum. The type of tests that we needed to perform for our hypothesis I learned about in IDEAS Lab. I learned how to use and operate the Instron machine while in the lab. This enabled me to help perform the tensile stress testing on our Kraft/OCC/BNCN samples. I also learned about surface properties and wettability angles in my biomaterials class. General engineering knowledge allowed me to perform the mathematical calculations needed to create charts and solve equations for this project i.e., wettability angle analysis. Statistical knowledge was also applied to find correct sample sizes and proper data presentation. As the project progresses, I would recommend further and more rigorous testing of all the metrics we defined last semester as well as a further narrowing down of our final product. Investigation into specific applications would allow us to begin to create a final prototype that has concrete dimensions and material specifications.

References

Web

Abitbol, Tiffany, et al. “Nanocellulose, a Tiny Fiber with Huge Applications.” *Current Opinion in Biotechnology*, U.S. National Library of Medicine, June 2016, www.ncbi.nlm.nih.gov/pubmed/26930621.

Andritsou, Vasiliki, et al. “Synthesis and Characterization of Bacterial Cellulose from Citrus-Based Sustainable Resources.” *ACS Omega*, American Chemical Society, 31 Aug. 2018, www.ncbi.nlm.nih.gov/pmc/articles/PMC6644481/.

Bajpai, et al. “The Reinforcement Mechanism of Bacterial Cellulose on Paper Made from Woody and Non-Woody Fiber Sources.” *Cellulose*, Springer Netherlands, 1 Jan. 1970, link.springer.com/article/10.1007/s10570-017-1468-6.

Bajpai, et al. “The Reinforcement Mechanism of Bacterial Cellulose on Paper Made from Woody and Non-Woody Fiber Sources.” Cellulose, Springer Netherlands, 1 Jan. 1970, link.springer.com/article/10.1007/s10570-017-1468-6.

Balea, Ana, Elena Fuente, M Concepcion Monte, Noemi Merayo, Cristina Campano, Carlos Negro, and Angeles Blanco. "Industrial Application of Nanocelluloses in Papermaking: A Review of Challenges, Technical Solutions, and Market Perspectives." *Molecules (Basel, Switzerland)*. MDPI, 25 Jan. 2020. Web. 02 Dec. 2020.

Barkho, G. (2020, September 23). How cereal nostalgia boosted Magic Spoon’s sales. *Modern Retail.*https://www.modernretail.co/startups/how-cereal-nostalgia-gave-magic-spoon-a-coronavirus-boost/*Biomaterials LLC*. 2019. Web. 02 Dec. 2020.

Boxed Water. (n.d.). *Our Product—Why Boxed Water is Better*. Boxed Water Is Better. Retrieved November 17, 2020, from https://boxedwaterisbetter.com/pages/our-product

Broten, Delores, and Jay Ritchlin. "The Pulp Pollution Primer." *The Pulp Pollution Primer*, Watershed Sentinel, 2012, watershedsentinel.ca/articles/the-pulp-pollution-primer/.

Cannabis Packaging Market—Growth, Trends, COVID-19 Impact, and Forecasts (2021—2026). (n.d.). Retrieved April 18, 2021, from https://www.mordorintelligence.com/industry-reports/cannabis-packaging-market

Carreira. P., Mendes, J.A., Trovatti, E., Serafim, L.S., Freire, C.S., Silvestre, A.J., Neto, C.P., 2011. Utilization of Residues from Agro-forest Industries in The Production of High Value Bacterial Cellulose. Bioresource Technology 102(15), 7354-7360.

Carter, C. R., & Rogers, D. S. (2008). A framework of sustainable supply chain management: Moving toward new theory. International Journal of Physical Distribution & Logistics Management, 38(5), 360–387. https://doi.org/10.1108/09600030810882816

Choi, Soon Mo, and Eun Joo Shin. "The Nanofication and Functionalization of Bacterial Cellulose and Its Applications." *Nanomaterials* , MDPI, 25 Feb. 2020, www.mdpi.com/2079-4991/10/3/406/pdf.

Chrzan. "Cannabis Packaging Market." Packaging World, 10 Dec. 2019, www.packworld.com/issues/business-intelligence/article/21105536/cannabis-packaging-market.

Cohen, J. (1987). *Pizza crown assembly* (United States Patent No. US4700843A). https://patents.google.com/patent/US4700843A/en

Crawford, Ronald L. "Lignin Biodegradation and Transformation." *The Quarterly Review*

Deepak , Verma, et al. “Biomass, Biopolymer-Based Materials, and Bioenergy.” ScienceDirect, 2019, www.sciencedirect.com/book/9780081024263/biomass-biopolymer-based-materials-and-bioenergy.

Dima, Stefan Ovidiu, and Al Et. “Bacterial Nanocellulose from Side-Streams of Kombucha Beverages Production: Preparation and Physical-Chemical Properties.” *Polymers*, MDPI, 18 Aug. 2017, www.mdpi.com/2073-4360/9/8/374.

DS Smith Paper. (n.d.). *Kraft Linerboard—DS Smith Paper*. DS Smith. Retrieved November 29, 2020, from https://www.dssmith.com/us/paper/offering/products/kraft-linerboard

Fuller, R. B. (n.d.). *Closing the loop: A Guide to Material Flows and Terminology*. 40.

Goyal, H. (n.d.). *Properties of Paper, (Paper Properties)*. Properties of Paper. Retrieved November 29, 2020, from https://paperonweb.com/paperpro.htm

Grathwohl, Cutter H. "Kombucha Biomaterials Preliminary Data." *Kombucha Biomaterials LLC*. 2019. Web. 02 Dec. 2020.

Heck, Michel. *Rethinking Packaging*. Market Report. Deutsche Post DHL Group, 2019.

Intron. “TAPPI Standards Tensile Testing of Paper.” Instron, 2020, www.instron.com.br/pt-br/testing-solutions/by-test-type/tension/tappi.

Jacobs. “Pulp and Paper Industry Energy Bandwidth Study.” *ITP Forest Products Report*, ITP & American Institute of Chemical Engineers, 2006, www.energy.gov/sites/prod/files/2013/11/f4/doe_bandwidth.pdf.

Johansson, Anna. “Correlations between Fibre Properties and Paper Properties.” Mater Thesis in Pulp Technology, KTH, 2015, www.diva-portal.org/smash/get/diva2:505453/FULLTEXT01.pdf.

JUST WATER. (n.d.-a). *Impact – Plant Based Plastic – JUST WATER*. Retrieved November 17, 2020, from https://justwater.com/impact-plant-based-plastic/

JUST WATER. (n.d.-b). *Our Packaging – JUST WATER*. Retrieved November 17, 2020, from https://justwater.com/ourpackaging/

Karppinen, Anni. “Water Holding Capacity - How Cellulose Fibrils Does It.” *Microfibrillated Cellulose*, 2017, www.exilva.com/blog/water-holding-capacity-how-microfibrillated-cellulose-does-it.

Kurosumi, A., Sasaki, C., Yamashita, Y., Nakamura, Y., 2009. Utilization of Various Fruit Juices as Carbon Source for Production of Bacterial Cellulose by Acetobacter xylinum NBRC 13693.Carbohydrate Polymers 76(2), 333– 335.

Liukkonen, A. (1997). Contact angle of water on paper components: Sessile drops versus environmental scanning electron microscope measurements. Scanning, 19(6), 411–415. https://doi.org/10.1002/sca.4950190604

Lu, Jue, Tao Wang, and Lawrence T. Drzal. "Preparation and Properties of Microfibrillated Cellulose Polyvinyl Alcohol Composite Materials." *Composites Part A: Applied Science and Manufacturing*. Elsevier, 13 Feb. 2008. Web. 02 Dec. 2020.

Magic Spoon. (n.d.). *High Protein, Low Carb, Healthy, Keto Cereal | Magic Spoon Cereal*. Retrieved November 28, 2020, from https://magicspoon.com/

Maultasch, J., & Maultasch, B. (1996). *Combined pizza box lid support and cutter* (United States Patent No. US5480031A). https://patents.google.com/patent/US5480031A/en

Mazareanu, E. (n.d.). *Parcel shipping volume worldwide 2013-2026*. Statista. Retrieved November 17, 2020, from https://www.statista.com/statistics/1139910/parcel-shipping-volume-worldwide/

Microcellulose gains foothold in paperboard—Paper Advance. (n.d.). Retrieved December 1, 2020, from https://www.paperadvance.com/blogs/mark-willliamson/microcellulose-gains-foothold-in-paperboard.html

Minter, A. (2020, July 27). *Yes, You Can Recycle Your Pizza Boxes*. Sierra Club. https://www.sierraclub.org/sierra/yes-you-can-recycle-your-pizza-boxes

Mordor, Intelligence. “Single-Use Packaging Market: Growth, Trends, and Forecast (2021 - 2026).” Single-Use Packaging Market | Growth, Trends, and Forecast (2021 - 2026), 2020, www.mordorintelligence.com/industry-reports/single-use-packaging-market#:~:text=The%20Single%2Duse%20Packaging%20market,the%20forecast%20period%202021%20%2D%202026.&text=The%20increasing%20adoption%20of%20single,growth%20over%20the%20forecast%20period.

Murphy, L., & Ebner, T. (2020, July 13). *AF&PA and Industry Partners Aim to Set the Record Straight – Pizza Boxes Are Recyclable, Grease and Cheese Not an Issue*. https://afandpa.org/media/news/2020/07/13/af-pa-and-industry-partners-aim-to-set-the-record-straight-pizza-boxes-are-recyclable-grease-and-cheese-not-an-issue

Nata De Coco Market Share 2019: Industry Size, Demand, Developments Trends, Growth Factor, Key Players Profile, Business Boosting Strategies by 2022 | Benzinga. (n.d.). Retrieved December 1, 2020, from https://www.benzinga.com/pressreleases/19/08/ab14253555/nata-de-coco-market-share-2019-industry-size-demand-developments-trends-growth-factor-key-players

Nelson, D. C., & Andrisin, J. J. (2007). *Pizza box lid support and serving aid* (United States Patent No. US7191902B1). https://patents.google.com/patent/US7191902B1/en

New Indy Containerboard. (n.d.). *What We Do | New Indy Containerboard*. Retrieved November 29, 2020, from https://newindycontainerboard.com/what-we-do/

Path Water. (2019, May 13). *Why Tetra Pak® Cartons Are NOT A Sustainable Solution for Bottled Water*. PathWater. https://drinkpathwater.com/blogs/news/10-sad-truths-about-cartons-like-tetra-pak%c2%ae-why-they-are-not-a-sustainable-solution-for-bottled-water

Reichert, Thomas. MILD KRAFT TREATMENT OF LINERBOARD, CORRUGATED MEDIUM, AND BOX PLANT CLIPPINGS, University of Washington, 1995, www.fpl.fs.fed.us/documnts/pdf1995/reich95a.pdf.

Schröpfer, Suellen Brasil. "Scientific Electronic Library Online." *SciELO*. Mar.-Apr. 2015. Web. 02 Dec. 2020.

Stora Enso. (2018). *Stora Enso Annual Report 2018*. https://www.storaenso.com/-/media/documents/download-center/documents/annual-reports/2018/storaenso_strategy_2018.pdf

Stream Study. 7.

Streditorial. (n.d.). *Facts About Clothing Labels*. Retrieved November 28, 2020, from https://www.streetdirectory.com/travel_guide/193739/modelling/facts_about_clothing_labels.html

Sun, Changquan (Calvin). “True Density of Microcrystalline Cellulose.” Journal of Pharmaceutical Sciences, Elsevier, 29 Jan. 2016, www.sciencedirect.com/science/article/abs/pii/S0022354916318676.

Surface Wetting and Pretreatment Methods | Adhesion Bonding. (2012, May 4). http://www.adhesionbonding.com/2012/05/04/surface-wetting/

TAPPI , and Muchorski. “Tensile Properties of Paper and Paperboard (Using Constant Rate of Elongation Apparatus) (Revision of T 494 Om-01) .” TAPPI Standards, TAPPI , 2006b, www.tappi.org/content/sarg/t494.pdf.

TAPPI. Forming Handsheets for Physical Tests of Pulp (Reaffirmation of T 205 Sp-02) , TAPPI, 2006a, www.tappi.org/content/sarg/t205.pdf.

Taylor, C. (2019, November 3). *Meet Tetra Pak, the most maddening piece of packaging in your kitchen*. Mashable. https://mashable.com/article/tetra-pak-recycle/

Terlau, Wiltrud. *Ecological Comparison of the Use of Sulphate Pulp, Wastepaper Material, and Grass-Based Pulp in German Paper Production*. Life Cycle Analysis Report. Sankt Augustin: Hochschule U, 2017. Print.

Tetra Pak. (n.d.). *Packaging material for Tetra Pak carton packages*. Retrieved November 17, 2020, from https://www.tetrapak.com/solutions/packaging/packaging-material/materials

Torvinen, Katariina. "Smooth and Flexible Filler-nanocellulose Composite Structure for Printed Electronics Applications." Research Gate, June 2012. Web. 2 Dec. 2020.

"The History of the Cardboard Box." *Attic Self Storage*. Jan. 2020. Web. 02 Dec. 2020.

US EPA, O. (2017, September 7). *Paper and Paperboard: Material-Specific Data* [Collections and Lists]. US EPA. https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/paper-and-paperboard-material-specific-data

Ververis, C., et al. “Fiber Dimensions, Lignin and Cellulose Content of Various Plant Materials and Their Suitability for Paper Production." *Industrial Crops and Products*, Elsevier, Oct. 2003, www.researchgate.net/publication/215612050_Fiber_dimensions_lignin_and_cellulose_content_of_various_plant_material_and_their_suitability_for_paper_production/link/5d66497d458515b5b41def36/download.

Virginia's potential $50 million medical cannabis program poised to launch. (2020, August 12). Marijuana Business Daily. https://mjbizdaily.com/virginia-potential-50-million-medical-cannabis-program-poised-to-launch/

Vitale, C. (1985). *Package saver* (United States Patent No. US4498586A). https://patents.google.com/patent/US4498586A/en

Webstaurant Store. (2020, May 03). EcoChoice Heavy Weight Compostable 6 1/2"

WestRock. (2016, May). *Domestic Standard Linerboard*. https://www.westrock.com/-/media/pdf/containerboard/product-guide/domestic-standard-linerboard-032016-v3-pdf.pdf

WestRock. (2020). *Incorporation of Post-Consumer Pizza Boxes in the Recovered Fiber Stream Study*. 7.

Williamson, Mark. "Mark Williamson." *Paper Advance*. 24 Jan. 2017. Web. 02 Dec. 2020.

Wnuk, P. (2020, February 3). *The Future of Apparel Labels*. Labels & Labeling.

Wyk, Van. "Nata De Coco Price Quotes." Awe Agric Trade, Aug. 2018. Web. 02 Dec. 2020.

Zambrano, F., Starkey, H., Wang, Y., Abbati de Assis, C., Venditti, R., Pal, L., Jameel, H., Hubbe, M. A., Rojas, O. J., and Gonzalez, R. (n.d.). *Using micro- and nanofibrillated cellulose as a means to reduce weight of paper products: A review :: BioResources*. Retrieved November 6, 2020, from https://bioresources.cnr.ncsu.edu/

Zeng, X., Small, D.P., Wan, W., 2011. Statistical Optimization of Culture Conditions for Bacterial Cellulose Production by Acetobacter xylinum

Human

Blankenship, C. (2021, March 17). Personal communication [Zoom Interview]

Hawboldt, M. (2021, March 29). Personal communication [Zoom Interview]

Schueller, G. (2021, April 12). Personal communication [Zoom Interview]

Fine, R. (Recurring). Personal communication [Zoom Interview]