INVESTIGATION INTO POLYHYDROXYBUTYRATE AND BACTERIAL NANOCELLULOSE COMPOSITES FOR SINGLE-USE PAPER PACKAGING

(Technical Paper)

A MULTI LEVEL PERSPECTIVE ASSESSING ALTERNATIVE CELLULOSE ADDITIVES IN PAPER PACKAGING

(STS Research Paper)

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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INTRODUCTION

Paper is a ubiquitous product integrated into nearly every global industry. While the paper packaging industry has made strides toward closed loop chemical recovery, fundamentally the conversion of plant matter into paper requires 3 times more water, produces 63% more emissions, and requires about twice as much material than compared to recycled paper fiber (Balea et al. 2020). At the current scale, corrugated cardboard and paperboard represent an ideal high performance product with high fiber recovery that could benefit from increased recycled fiber utilization. The technical component seeks to leverage existing biomaterials to create additives aligned with industrial manufacturing infrastructure and practices that don't require change to current consumer behavior for adoption.

Disruptive external forces - in the form of stricter recyclable importation policies enacted in China - combined with increased market demand spurred by the rise of e-commerce have caused price and demand dislocations for recycled and 'virgin' paper fibers. Beginning in 2017, China dramatically reduced importation of recovered recyclables from the United States and Europe. Known as the National Sword Policy, China enacted a new contamination limit at 0.5-1.5% which caused decreases in imports of waste plastic by 99% and waste paper by 33% (Resource Recycling, 2018). This rapid shift caused price disruption in recycled material commodities.

Meanwhile, environmental policy initiatives in the EU have created a "technology-push" for sustainable, biobased products in the packaging industry by implementing a collaboration with the Biobased Industries organization in Europe (BBI-JU, 2020). In addition to this €3.7B private-public sponsored fund, "demand-pull" instruments such as the single use plastic ban for select products to go into effect in 2021 have generated supply chain shifts initiated by large stakeholders like Fast Moving Consumer Goods (FMCG) companies such as Adidas and Ikea (Kramm et al., 2018; Rankin, 2019).

The formation of policy support structures that drive market readiness must create collaborative environments that mobilize and motivate industrial producers and entrepreneurs in order to comprehensively integrate sustainable paper packaging technology into production (Hasenauer et al., 2016). This balance of politically led capital injection, external market trends, and industry cooperation relies on promoting technological and manufacturing readiness and distributing value across stakeholders economically, environmentally, and socially. The STS topic investigates case studies surrounding early stage emergent innovations of paper packaging additives.

A Multi Level Perspective (MLP) lens developed by Geels & Schot in 2007 is bolstered by a Technological and Market Readiness Levels (TRL & MRL) published by Hasenauer et al. in 2016 to provide a framework for holistically assessing influence and transformation of innovation commercialization within paper packaging (Geels & Schot, 2007; Hasenauer et al., 2016). Additionally, the concept of technology/product oriented movements (TPMs) developed by Dr. David Hess in 2005 will be explored in the context of interpreting a niche entrepreneurial case study in this industry (Hess, 2005).

Technical Topic

Over 92% of cardboard is recovered making it the highest recovered recyclable of any material by far (*AF&PA*, 2020). Due to cardboard's physical consolidation along the supply chain and the fibers' high mechanical performance, Old Corrugated Cardboard (OCC) is recycled and then reintegrated into the manufacturing process. OCC fiber accounts for 50% of all pulp used to make cardboard and using these fibers reduces raw material cost, energy consumption, and effluent/emission release (*DOE*, 2006). Since cardboard makes up 54% of all paper production, OCC reuse is vital to limiting negative impacts in an industry that accounts for 20% of all toxic US air emissions and 6% of global energy expenditure (*EPA*, 2017; Jobien et al., 2013). To maintain cardboard quality, the other 50% of pulp must be 'virgin' fiber derived from the Kraft process. The Kraft or sulphate process produces mechanically strong cellulose fiber from raw plant matter; however, with a yield of 30-70% by weight, the constant introduction of Kraft pulp creates an open loop system that accounts for the majority of energy expenditure and toxic emission and effluent releases (Vakkilainen et al., 2012).

Mechanical Properties of Composites

The technical portion of the capstone, cosponsored by Kombucha Biomaterials LLC and Transfoam LLC and guided by Professor James Groves, aims to extend the life cycle of OCC fiber and reduce the Kraft pulp fraction used in cellulose packaging while maintaining mechanical performance standards by employing biomaterial additives. I am responsible for producing composite OCC-Kraft blended pulp lab test sheets. These sheets will be formed with wet end introduction of 1% dry weight bacterial nanocellulose (BNC) or Polyhydroxybutyrate (PHB) in compliance with the Technical Association of the Pulp and Paper Industry (TAPPI) standard T205. (*TAPPI*, 2006)

Ratios of (OCC-Kraft) pulp will range (60%-39%), (80%-19%), and (90%-9%) in addition to the 1% PHB or BNC. The weight of all samples will be 250 grams per square meter (GSM) in accordance with typical cardboard bulk values (Mybox, n.d.) Both BNC and PHB are biodegradable polymers that in small amounts (1-5%) have been shown to enhance mechanical and barrier properties of paper critical for cardboard packaging such as tensile strength (Arévalo et al, 2016; Ondaral et al, 2015). These composite sheets will undergo tensile testing on an Instron® 5543 according to TAPPI Standard T494 and will be compared to a (50%-50%) control sheet that will benchmark performance to current industry standards. Metrics for end product success will be determined by relative strength increase compared to the control sheet that should exhibit ~500 N/mm and will be empirically confirmed according to TAPPI Standard T494 (Roman, n.d.)

Industrial Properties of Composite Additives

Additionally, it is important to consider potential disruption to processing line practices to make a convincing case for adoption in a large scale commodity industry such as cardboard. A key factor in the operation of a paper mill is the speed at which the fourdrinier machine is capable of running while producing sufficiently dry paper at the output. Since pilot scale fourdrinier machines are unavailable, testing the same pulp dispersions previously detailed for dewatering time will indicate potential success or barriers for BNC or PHB at industrial level. Dewatering time refers to the amount of time it takes for the free solution to drain from a column of pulp and will be assessed according to TAPPI T221 (*TAPPI,* 1999). Success would be indicated by similar dewatering times that are statistically significant between control samples and biomaterial additive infused samples.

STS Topic

Landscape

Cellulose is the most abundant biopolymer on the planet, and is a natural, biodegradable material that is currently integrated into large industries such as packaging. 35% of all packaging in the United States is cellulose based. External, landscape pressures from consumer preferences, e-commerce, and geopolitical shifts suggest that cellulose packaging will gain increased market share in response to petroplastic reduction agendas (Bukowski et al, 2018). Paper production is projected to grow from 422M metric tons in 2019 to 495M metric tons in 2030. (*Statista*, 2020) With the increase in e-commerce, packaging has undertaken a dominant role as the primary form of physical customer interface, and customers' perception of sustainable packaging has impacted FMCG brands. 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 (*DHL*, 2020). Similarly, FMCG companies such as IKEA, Adidas, and Colgate-Palmolive have announced plans to transition entirely to recyclable, biobased packaging by 2024-2025 (*DHL*, 2020). Not coincidentally, all of these companies are european based and this apparent market shift has been galvanized by technological-push and market-pull strategy enacted by the EU.

Recyclable product policy changes in the EU have altered the course of paper packaging. Regulatory changes in the EU, such as the reduction of fossil-fuel subsidies and polluter based tariffs, represent landscape pressures exerted to encourage private industry to adopt more sustainable practices fostering an increased MRL (Geels & Schot, 2007; Hasenauer et al., 2016). Both MRL and TRL were originally developed by NASA as a numerical scale (1-9) to illustrate the technological readiness pathway from concept to infield deployment (Wheeler, 2010). Hasenauer specifically adapted this concept to apply beyond technological readiness and include market readiness. He also empirically demonstrated that niche technology adoption was most successful when MRL was higher than TRL, meaning that potential customers are willing to purchase an fledging innovation that is under development. Simultaneously, a technological-push, through increased investment in biobased industries, was fomented between the BBI and the EU. Known as the Biobased Industries Joint Undertaking (BBI-JU), €3.7B was raised for the development of the biobased economy with the explicit aim to: foster biomass feedstocks that did not compete with food, optimise the economic viability of flagship biorefineries, and develop biobased products implementable into the market (BBI-JU, 2020). Additionally, further capital incentives were established to incentive corporations to provide benefits to social stakeholders such as job creation to citizens in rural areas.

In conjunction with EU initiatives, recyclable importation tightening through the National Sword policy exacerbated the need for paper packaging innovation. China - which burned high volumes of recyclables - cut importation of waste paper by 33% and an oversupply of OCC dropped prices from the high of $180 per ton to historic lows under $25 per ton. (EcoTechnology, 2018; Katz, n.d.; Resource Recycling, 2018) This policy change exposed recovered recyclables' reliance on exportation for economic viability and created a window of opportunity for circular paper innovation integration through more efficient utilization of the prevalent OCC fiber.

Regime

Among the incumbent players capital support from the BBI-JU materialized via the Exilva Project. Exilva was €44M project spearheaded by the multinational biorefinery conglomerate Borregard and represented a collaboration among some of Europe's largest paper producers (Stora Enso and BillerudKorsnäs) to produce Microfibrillated Cellulose (MFC) at an economically industrial scale (Exilva, 2020). MFC is a nanoscale cellulose fiber discovered in the 1980's and is similar to BNC. It is derived from wood pulp through energy intensive mechanical shearing and chemical treatment (Lu et al., 2008). When introduced to paper in proportions as low as 1% dry weight it exhibits properties such as increased (+25%) tensile strength; however, the high cost of production has historically kept MFC reserved to lab scale experiments and a lower TRL than was necessary for industrial development (Xiang, 2017).

With the capital incentive of the Exilva project, MFC incorporation into packaging is undergoing trials with Stora Enso producing 500,000 tonnes of paperboard containing MFC that will be converted by BillerudKorsnäs into lightweight milk cartons (Williamson, 2017). The commercial integration of MFC 40 years after it's discovery is directly tied to the landscape policy support as evidenced through the rural job creation emphasized by these large corporations. Additionally, monetary incentives offered by the EU to reduce weight and increase recycled fiber content in packaging (both qualities that MFC possess) represent demand-pull strategies that: create value for all stakeholders in the distribution chain, increase market appetite, and forward technological development(Williamson, 2017). Figure 1 shows quotes from key positions within these companies highlighting the effect that landscape support has had on the development of this industrially intensive regime level project (Songer, 2017).

Tom Egenes, Director of Strategic Sourcing at Elopak (drink carton manufacturer partnered with Stora Enso), says, "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." (Songer, 2017)

Jarle Wikeby, Exilva Project Coordinator, says, "For Exilva, the backing of an organisation the size of **BBI JU has strengthened our confidence in the project and boosted support from our board**." (Songer, 2017)

Mats Hjrnevik, marketing manager of Borregaard (lead company for Exilva project), says, "**I think the support the BBI JU brings is a key risk mitigator**; with the EU showing that they really stand behind us, and truly mean it when they say they want to support more sustainable technologies. That's key for companies like us to be able to succeed." (Songer, 2017)

Figure 1 Quotes on BBI-JU involvement in Regime Level Actors

Niche

The BBI-JU has also created opportunities for capital investment in innovations outside the loci of incumbent actors. Hess introduces the concept of TPMs in which entrepreneurs create technology in conjunction with social movements like the focus toward sustainable materials (Hess, 2005). Creapaper is a small company that utilizes switchgrass locally grown on economically unproductive, fallow land to create an alternative cellulose feedstock for paper. Sourcing raw material locally cuts down on supply chain emissions and creates additional revenue streams and jobs for rural farmers and landowners. This social value combined with the fact that Creapaper fiber production uses: 75% less energy, no chemicals, and 1% of the water required for traditional wood fiber processing earned Creapaper a €2M grant from the BBI-JU (Creapaper, 2020; Terlau, 2017). However, breaking into this position was not without challenges described by Geels and Hasenauer. These barriers known as "rules of the game" by Hasenauer are imposed by regulatory bodies and industry actors that can prevent new innovations from entering the market. In the beginning, no paper producers would use Creapaper fiber since it didn't have material certifications and it was feared that the new material would damage their machinery. D'Agnone, the founder, established a relationship with Bonn University to garner technological credibility. Through this relationship, Creapaper has been able to break into the paper industry and is now listed as a standard material on the european paper index. Now 26 factories currently use their fiber since emission reductions offer EU incentives for paper producers and grass based paper generates positive sentiment from consumers (Jurgs, 2017). Hess describes this TPM pathway as a private sector symbiosis where innovations produced by social movement led entrepreneurs are successfully integrated into industry practices (Hess, 2005). Furthermore, between these two case studies exist overlapping and reinforcing interests. Currently, the grass fiber content is limited due to mechanical performance and MFC has been demonstrated to improve tensile strength (Creapaper, 2020). The addition of MFC could allow for an increase in grass fiber content creating value for stakeholders like: rural farmers, entrepreneurs, biorefineries, distributors, and consumers while exhibiting a lower environmental impact that aligns with current EU initiatives for creating sustainable paper packaging.

Next Steps

- Quantify jobs created by MFC in the Regime Level
  - Quality/skill level of jobs, location of jobs created
- Quantify jobs created by Creapaper in the Niche level
  - Jobs created in rural areas, percentage increase in revenue stream for farmers and landowners
- Determine success of first phase MFC trials
  - Determine cost of MFC, cost of raw fiber
  - Amount of fiber saved, equivalent emission, energy, and money savings
  - Determine scale of MFC and plans for grow
- Research Hess theory for symbiosis between social movement TPM and Incumbent actors
  - Determine strength of financial alignments between Multinational conglomerates and Creapaper
  - Does the adoption of MFC and grass fiber actually threaten these actors?

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