# [UNFINISHED ROUGH DRAFT] Lost In The Sauce
# Biodegradable Condiment Package Coating

ChemBE Product Design
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## BACKGROUND

In the United States, around 35.7 million tons of plastic is produced each year, which is enough to fill a professional sports stadium in half a day [a]. Much of this production, around 30%, comes from packaging materials that are used once and subsequently tossed [b]. Plastic is favored for its cheap cost, ease of manufacturing, and tunability. As such, nearly all packaging materials are reliant upon these unsustainable materials.

Our company, Lost in the Sauce, is looking to overhaul the current packaging materials market by engineering biodegradable or compostable plastic alternatives. We have chosen to focus on a niche issue in packaging for our first product: condiment packets.

Each year, an estimated 855 billion single-use condiment packets, enough to cover the surface of the earth, end up in landfills [c]. These packets are made from aluminum and plastic films, which are impossible to recycle and take hundreds of years to decompose. While sustainable packets do exist, there is currently no sustainable options compatible with liquids or acidic components such as ketchup, mustard, and mayo. Liquid and acidic components pose unique challenges that we intend to address. We believe our proposed solution has the potential to change the fundamental nature of the 30 billion USD/year market that currently exists for condiments and sauce sachets [n].

<u>Relevant Trends</u>

The quick service restaurant industry, the main market utilizing single-use condiment packets, has an estimated 267 billion USD market size and is continuing to grow [d]. There are roughly 200,000 fast-food restaurants in the US alone and another 13,000 food courts - both public and private [e,f,g]. Of these institutions, 70% have indicated that sustainability is a priority, but only 41% report taking actionable steps to reach this goal [h]. This demonstrates a severe lack of feasible options for businesses to utilize, creating an open space in the market for our product.

Historically, around 150 years ago, there was no garbage, certainly in rural areas. Sacks and wood boxes were reused. Bottles were washed and reused. Paper was used multiple times until it had little body left and was buried and ultimately broken down. In today's world, plastic is found anywhere and everywhere and because of that our landfills are constantly filling up dangerously.

Our company solves the issue of the millions of pounds of plastic pollution resulting from package use. The current makeup of packages (including condiment packets) makes them nearly impossible to recycle, and we aim to devise an alternative packaging that is biodegradable to end the pollution that the current packages are adding to.

Our ultimate target is modifying all types of packaging to be recyclable. However, we are starting with changing condiment packaging since it is a good reference case for other packaging types and represents a good first step to a much larger issue. This is a problem that everyone can understand and care about.

Target Market:

Essentially, every restaurant that uses condiment packages has this problem, which is hundreds of thousands. Our initial target market is college dining halls as they tend to have greater sustainability goals than restaurants. As college students, we have already begun discussing these goals with the Johns Hopkins University Head of Sustainability who has shown interest in our product.

While it is difficult to get an estimation of the size of distributors, we know that 855 billion packets are used each year, and the condiment and sauce packet industry has a size of 30 billion USD/year [c, n]. Specifically, if we are to aim at distributors for college dining services and other food court style businesses, we would be looking at a total of 13,000 possible end-user organizations [e,f,g]. Our target would be the condiment distributors for these organizations, but our product would be designed for use in these 13,000 food court venues with the hope that their preferences influence the products that distributors manufacture and sell.

The relevant stakeholders for this problem include:

- *Fast food restaurants*: they are large consumers of condiment packaging and contribute to a lot of waste by offering the packets to their customers.
    - Example: Taco Bell goes through ~8.2B of sauce packets in a year [k]

- *Condiment brand companies*: they are another large contributor to the condiment packet waste
  - Example: Heinz sold 11B condiment packets in a year [l]
- *Manufacturers*: they are in charge of actually creating the packet itself
- *Distributors*: they supply a vast network of customers such as restaurants, food courts, and grocery stores with the packets once they are manufacturers
- *Government regulators for food safety and sanitation*: Ensure food packaging that comes into contact with food is safe for human consumption
  - Example: FDA's Center of Food Safety and Applied Nutrition and the Food Safety and Inspection Service [i, j]
- *Waste collectors and municipalities*: they collect the waste, including condiment packets, and transport it to a landfill
- *Consumer*: while the consumer is usually not buying the packets themselves, their user experience will play a large role in determining the effectiveness of the packet
  - Example: does it tear open readily, taste of condiment inside, do they prefer a sustainable option and does that change their consumption behavior, etc.

## MANUFACTURING PLAN

Our manufacturing plan consists of three main parts: (1) Synthesizing the Whey Protein Isolate coating solution, (2) Dip coating the (PAPER OR OTHER) into the solution and (3) Folding the package and adding perforations.

**Synthesis of Whey Protein Isolate Solution**

10 g of WPI and 5, 10, or 15 wt% of Ascorbic Acid (based on a WPI dry basis) were dissolved in 100 mL of Milli-Q ultrapure water at 80 °C and stirred at 200 rpm for 30 min. Then, Glycerol was added (50 wt% on a WPI dry basis), the pH was adjusted to 10 using 1M NaOH, and the solution was heated at 80 °C for another 30 min under magnetic stirring.

**Dip Coating Manufacture Method**

The paper will be dip-coated in the WPI solution with a barrier on one side of the material so that both sides aren't coated. The paper will be dipped into the solution and then withdrawn. The reasoning for this withdrawal speed and the modeling of this process will be explained in detail in the following section. Once removed from solution, the coated material will be left out for 24 hours to dry.

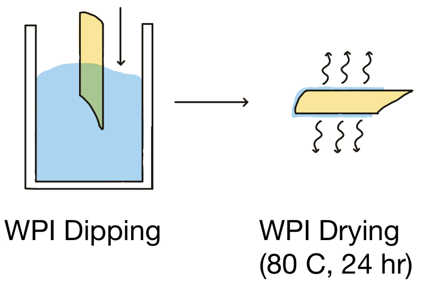


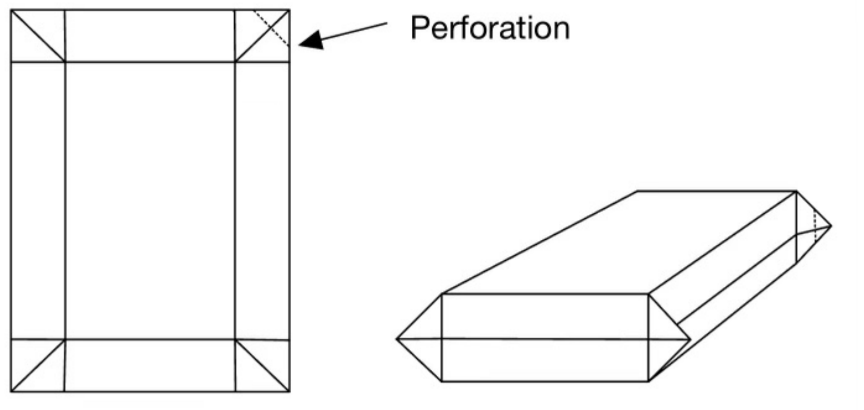

**Figure X. Schematic of surface treatment of package material using dip-coating process**

To ensure uniformity of the coating during drying, several techniques can be employed. The material can be placed on a smooth inert surface, such as glass, and uniformly weighted. The temperature, pressure, gas composition, and gas flow regime of the drying environment will have an effect on the resulting film. These variables require testing to ensure ideal conditions, but for initial tests standard room temperature conditions will be sufficient. Once dried, the material will undergo a secondary inspection to search for any defects. The pieces that pass the secondary inspection will be ready for assembly/folding**.**

Additional coating steps may be applied to produce multiple layers that can affect the performance and manufacturing/folding of the material. These additional steps may involve materials other than whey protein isolate to create a layered composite material.

**Package Folding and Perforation Addition**

The newly coated paper-based material will then be scored along specific lines using shallow cuts or indentations along intended fold lines. At this point, perforations that allow the user to tear away a section of the corner to squeeze out the condiment will be added using a sharp blade to cut through the material to make a line of little holes. After scoring, the paperboard will be folded along the predetermined lines so that it forms a box-like structure that we have designed. *A biodegradable adhesive will be applied to certain areas of the material during the folding process, to help ensure that sturdiness is maintained. (not sure about this)*




**Manufacturing Scale-Up**

While our project focuses on the initial development of the “juice box” condiment packet and manufacturing on a small, non-commercial scale, it is important to consider scale-up possibilities for our business model to be realistic. Adopting common practices from current milk, juice, and other carton production, we can break large-scale manufacturing into two processes: (1) “mother-roll” production and (2) carton filling [m1].

The “mother-roll” is a large sheet of material that is to be cut and folded into cartons that can be filled with the material of interest. These rolls are produced in large quantities with layers, printings, and perforations added prior to cutting into individual, unfolded boxes. For our material, the addition of perforations and printing is trivial and easily produced by templates already used in manufacturing. The layering of the mother-roll with our whey protein coating requires adaptation to current rotary coating or multiple dip coating machines, which may pose a significant or costly issue for manufacturers in the future [m2].

Once the mother-roll is produced, printed, and cut, it can be folded and filled with a singular machine. This process typically occurs at a facility specialized for packet filling that is separate from the facility that produced the mother-roll [m1]. The filling machines take the cut-mother roll and rapidly fold/fill them in one step. They have been widely adapted to handle packages of varying geometries and materials [m1]. An example of these machines can be seen in Tetra Pak, one of the largest packaging companies in the world that specializes in filling and folding carton packages [m3].

These existing carton manufacturing practices demonstrate compatibility with our product and suggest that scale-up is possible. This knowledge provides further confidence in our current model and product design.

## MODELING/TECHNICAL ANALYSIS

### Whey Protein Background

The dairy industry generates substantial volumes of liquid waste referred to as dairy whey (DW) during the casein coagulation process. This precipitation can be induced through microbial growth (i.e. cheese whey production), acid addition (i.e. acid casein manufacture), or enzyme addition (i.e. rennet casein manufacture). DW, primarily sourced from bovine milk, contains valuable nutrients and can be repurposed into edible films or coatings, leveraging its protein-rich composition. Soluble milk proteins constitute approximately 20% of the total milk protein content in DW, with five major types identified: β-lactoglobulin (β-Lg) comprising 50%, α-lactalbumin (α-La) 20%, glycomacropeptide (GMP) 15%, immunoglobulin (Ig) 10%, and bovine serum albumin (BSA) 8%. Whey protein isolate has the highest level of purification, with over 90% protein content on a dry weight basis, which is optimal for film formation.

Whey protein films are entirely biodegradable, with one study finding that WPI films buried in a compost pile started to see degradation in 2 days, with 80% of the total solids lost after 7 days. WP films and coatings have been utilized in various food items like peanuts, walnuts, frozen salmon, fruits, and breakfast cereals to enhance aroma, fat, moisture, and gas barriers. We aim to formulate a WPI coating compatible with packaging applications for liquid products, particularly condiments.

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### Whey Protein Structure

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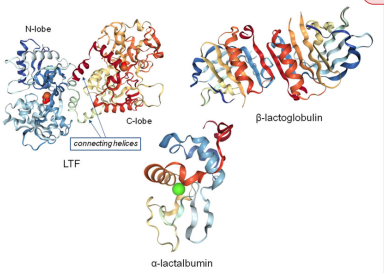
Whey protein consists of compact secondary, tertiary, or quaternary globular molecules with various combinations of cross-sulfur bonds. It exhibits characteristics such as being heat-labile, dephosphorylated, and less susceptible to calcium. Monomeric β-lactoglobulin (β-Lg), a small globular protein with a defined secondary and tertiary structure, consists of 162 amino acids, including five cysteine residues. Among the cysteines, four participate in forming two S-S bonds, while the remaining one (Cys 121) retains a free thiol group, strategically positioned within the native β-Lg structure. This is important for film formation. Various factors, including charge density and the balance between hydrophilicity and hydrophobicity, can alter the conformation of whey protein (WP), which influences the physical and mechanical attributes of resulting films or coatings.




### Whey Protein Film Formation

WP film primarily constitutes a dry, highly interactive polymer network with a 3D gel structure. WP's globular structure can transform into relatively linear configurations, forming irreversible aggregates through thiol-disulfide exchanges. The formation of the film involves dissolving whey protein isolate (WPI) in distilled water, adjusting the solution's pH if needed, and heating the solution for protein denaturation. Denaturation exposes the functional and hydrophobic groups of WP, facilitating the formation of a 3D chemical network that promotes intermolecular S-S bonding and hydrophobic interactions during drying. The majority of hydrophobic and thiol (SH) groups are buried within the protein molecule's center, so denaturation is crucial for a stronger film formation.

While native WP can form films, it relies on low-energy bonding mechanisms, such as electrostatic interactions, hydrogen bonding, or van der Waals forces. Whey protein films produced without heat treatment are prone to breaking into small fragments during drying, owing to weak intermolecular interactions.

### Addition of a Plasticizer

Adding plasticizers is crucial when producing protein films to prevent fragility caused by excessive protein network cross-linking. Plasticizers are low molecular mass, non-volatile agents and are incorporated into polymers to modify their physical and mechanical characteristics. Common food-grade plasticizers include monosaccharides, disaccharides, polyols, lipids, and water. When crafting edible WP films or coatings, plasticizers are a standard inclusion as pure WP films tend to be brittle and rigid due to strong interactions between polymers. Because they reduce the intermolecular interactions among protein polymers, they improve the flexibility, elongation, toughness, and tear strength of WPI films.

However, the extent of film flexibility depends on the type and concentration of plasticizers, with increased flexibility often resulting in elevated water vapor permeability (WVP), which is undesirable in liquid food packaging applications. Typically, edible WP-based films or coatings contain plasticizer levels ranging from 10% to 60% (w/w). However, these levels are contingent upon the desired film properties and the type of plasticizer employed.

Although whey protein films exhibit excellent barrier properties against oil, aroma, and oxygen, they are insufficient as a moisture barrier, due to their hydrophilic nature. Incorporating lipid materials such as fats and oils into whey-based films can enhance their hydrophobicity, which improves their effectiveness as moisture barriers. Commonly utilized lipid materials include plant oils, waxes, fatty acids, and acetylated monoglycerides.

**Barrier Specifications: Oxygen Transfer Rate**

The oxygen transfer rate refers to the rate of oxygen delivery from a gas into a liquid. This measure is crucial in food packaging because exposure to oxygen can cause oxidation, ultimately degrading the food quality.

The desired oxygen transmission rate (OTR) value for papers in most food packaging applications is below 10 $cm^3/m^2 \cdot day \cdot bar$ at 23°C and 50% relative humidity (RH). Another source suggests that the industry standard for high oxygen barrier packages is an OTR of less than 15.5 $cm^3/m^2/24$ hr (or 1 $cm^3/100\ in^2/24$ hr).

**Barrier Specifications: Water Vapor Transmission Rate**

The water vapor transmission rate measures the amount of water vapor that passes through a material over a specified period. WVTR is vital in packaging materials, as water vapor permeating packaging will affect food freshness and microbial growth. Moisture also

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$$WVTR = \frac{m \cdot l}{A \cdot t} \text{ [Equation xyz]}$$

Where $m$ is the mass of water that permeates a film at steady-state, $l$ is the thickness of the film, $A$ is the area of the film, and $t$ is time, at a given temperature and relative humidity value.

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**Dip Coating Process**

Dip coating is a method of depositing a desired solution onto the surface of a substrate with a desired film thickness. In our case, we will be uniformly depositing our Whey Protein Isolate (WPI) solution onto a paper-based material. We will provide a model of this dip-coating process since there aren't well-known industrial-level versions of this process. To simplify the model, we will need to make some assumptions, although they are justified. As a result of this modeling, we can make predictions about the outcome of the dip-coating and engage in a later analysis involving it.

**Necessary Equations**

$$\boldsymbol{h_f} = k\frac{E}{LU_O}, k = \frac{cM}{\alpha\rho} \text{ [Equation xyz]}$$

where….

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**Initial Experiment for Formation of Whey Protein Film**

Previous studies have developed whey protein films by dissolving WPI in distilled water at concentrations ranging from 5% to 12%, adjusting the pH of the solution to slightly basic levels (around 7 or 8), and heating it between 80°C and 90°C for 10 to 30 minutes to denature the protein. In another study, a film was formed using a 10% WPI concentration, heated at 90°C for 30 minutes, and subsequently dried for 4 hours at 60°C. Additionally, researchers introduced glycerol as a plasticizer at a 60% concentration of WPI after subjecting the film to heat treatment. Our initial methodology was based on this previous research.

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On April 18th, 2024, we conducted an initial experiment for whey protein film formation. We did not include a plasticizer for this run, as we wanted to see how the whey protein interacts in our lab setup. First, we measured 20 grams of whey protein isolate from ****. We then dissolved the WPI in 200 mL of deionized water, using a magnetic stirrer, until a cohesive solution was formed at a pH of ~6. We did not adjust the pH to see how the whey protein would initially interact. Next, using serological pipettes, we placed 10 mL of the dissolved whey protein solution into a petri dish. We tried to ensure consistent thickness of the solution across the petri dish, using a cell spreader. We then placed the two prepared Petri dishes on a hot plate for 30 minutes, heated at 90 degrees. We left the Petri dishes to dry overnight (~24 hours at room temperature).

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In this first run, we found that while our film did form, it was very brittle, and broke while drying into large pieces. We also tried the dip-coated method with our WPI solution, using cardstock paper cut into a circle to fit the petri dish. Using tweezers, we dipped the cardstock into the solution for about 10 seconds, putting the coated cardstock into a petri dish to be heated, using the same heating and drying methodology we used for the single films.

**Future Work Recommendations**

Our methodology for protein denaturation may not have been uniform across the film as we used a hot plate which is only hot on one side of the film. We recommend in future experiments to use a lab-safe oven at 90 °C so that the film is uniformly heated. If we are still constrained to using a hot plate, we would heat the WPI solution in a beaker on the hot plate, while continuously stirring, before setting the solution in the petri dish to then dry, which may better uniformly denature the whey protein. Our initial trial found the film to be very brittle, underscoring the need for a plasticizer for better functionality as packaging. We recommend using a lipid plasticizer, such as beeswax or vegetable oils, which are both cost-effective options and have proven to decrease the water vapor permeability of the film due to its hydrophobic nature. The plasticizer would be added to the heat-treated WPI solution and then placed in petri dishes to dry. Another way to decrease the water-vapor permeability would be to treat the film with ultrasound, rather than just heat-treated.

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**FINANCIAL ANALYSIS**

Operational Costs

In the short term, our product costs mainly focus on R&D and marketing. We will require a rental laboratory space to synthesize, characterize, and test the applications of new packaging materials. This R&D cost would include the cost of equipment rental or usage fees, as specialized equipment is required to test the material's permeability, mechanical attributes (shear and tensile strength), physical characteristics, and structure. The other main cost in R&D will be raw materials, as many experimental chemicals have high costs due to low economies of scale. This, combined with the amount of materials we intend on testing, comprises a significant cost in our business venture.

Additional marketing costs exist to produce and deliver our product, including fees to register for product expos, signs/posters or other marketing materials, travel expenses, and a sales team. We would expect to ship samples across the United States which may incur a significant cost as well. Our team anticipates a high cost of travel to visit manufacturing sites to determine the feasibility of producing our product on a large scale.

Finally, we anticipate some administrative costs associated with our product. Since our packets are intended to be used with food products, we must register the packets with the FDA. Additionally, we expect to hire legal counsel to assist us in protecting our intellectual property, or ensuring a fair contract with any distributors or collaborating organizations.

Additional Cost Considerations

An exact figure for many costs is difficult to decipher as our product is still in development. However, we can use the production costs of a well-known polymer, PLA, to estimate our costs. The total cost of PLA production from cassava starch to PLA resin is $2,890 per ton [cost1]. Of course, our production would initially be more expensive due to its novelty, but this is a reasonable long-term unit price. Because we are developing a product with a pre-existing demand, as illustrated by the attempted development at Unilever and multiple sustainability goals by large companies (Heinz, Taco Bell, etc.) we believe that acquiring long-term customers will present little to no cost. In addition, since our business model starts with college dining services, including locally at Johns Hopkins University, we anticipate free advertising for us with school articles on switching to sustainable condiment packages.

The other relevant costs we may experience include manufacturing costs. While we intend to license our materials directly to a distributor or condiment manufacturer, if we choose to manufacture our product directly this will require a contract with a CMO, which is a significant cost.

Cost Estimates and Use of Funds

In the near term, we anticipate a cost of 600,000 USD to begin our business venture. Of this 6000,000 USD, we anticipate 110,000 USD for R&D development, split between lab rental (~5000 USD/month) and materials cost (50k USD). Additionally, marketing costs may incur 250,000 USD including the cost of a sales representative. The remaining initial cost is split between the team salary (50k USD/each) and legal fees for IP protection and FDA approval (30k USD). These costs initially can be very low due to the resources provided by Johns Hopkins University and the Chemical and Biomolecular Engineering Department.

As this business grows and begins to separate from Johns Hopkins, we anticipate significantly higher costs of business. We anticipate around 1.4 million USD will be required for the first campaign growth costs. This includes 500,000 - 700,000 USD for laboratory purchases, which is the standard cost allotted to university faculty for start-up labs. Another 200,000 USD will be split for materials and development from bench scale to manufacturing scale production. Manufacturing costs may cost upwards of 500,000 USD but may vary depending on process development and manufacturing requirements. Marketing costs at this point may rise into the tens to hundreds of thousands, as we must product test our material and ensure contact with the correct organizations.

Source of Funds

We will first look for initial funding from Johns Hopkins resources, such as grants like Campus as a Living Lab program and from HopStone Capital. After receiving an initial amount of money from these grants and showing success with our research plan, we plan to take advantage of Hopkins' accelerators (i.e. Spark or Fuel Accelerator) from Fast Forward U, which we can consider applying for and receiving grant funding. National sustainability research grants given by the United States Environmental Protection Agency offer additional funding options.

While VC funding may be harder to raise at this stage, we can also reach out to smaller and student-focused VC funds/programs like A Level Capital, Contrary Capital, Pear VC, Rough Draft Ventures, and Dorm Room Fund. Some funds are focused on cleantech and sustainability startups like Rocket Fund from Caltech which gives non-equity grants.

Lastly, we can look for angel investors from our networks and also broader angel networks. We understand that at different steps of the journey, the sources and amount of money will change depending on which step we are on, and anticipate often proving ourselves to additional investors for more funding.

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