Safer Alternatives to Laundry Detergent Packaging

ECOS Final Report

Mariana Mtanous Sanchez, Alex Shing, Deborah Chhun, Riya Dutta, Erin Sori Kim

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1. Abstract

Plastic packaging, especially high density polyethylene (HDPE) and polyethylene terephthalate (PETE) based packaging, is prevalent in today's society and demand continues to rise (Jiang & Bateer, 2025). HDPE and PETE are well-suited for packaging due to their high strength and excellent barrier properties making them effective for laundry detergent containers. Additionally, plastic packaging poses many human health and environmental risks, stemming from its persistence as microplastics and presence of toxic additives. To make their packaging more sustainable, ECOS, a company committed to producing safer household cleaning products, aims to reduce HDPE and PETE in their packaging and use safer materials. In response to this challenge, we developed a carton-like strategy that combines a base for structural support and a coating for barrier properties, enabling us to meet the diverse technical requirements for detergent packaging. Current cartons pose hazards in their production and disposal, prompting us to identify alternative materials that are both safer and more structurally sound for larger packaging. Our three strategies propose multilayered containers built of: (1) bamboo particles composite with PLA and MMT (industrially compostable); (2) zein and cutin (biodegradable and compostable); and (3) a PHA blend (biodegradable, compostable, and recyclable). Our approach is novel in that it replaces the incumbent virgin plastic with a multilayer, carton like system that separates structural and barrier functions. While these materials have been studied elsewhere, their combined application at this scale has not been widely explored in the laundry detergent industry. In this project, HDPE is used as a conservative benchmark for material comparison rather than a minimum performance requirement, recognizing that materials with lower performance may still be sufficient for packaging applications.

2. Introduction and Approach

2.1 Background

The goal for this challenge is to reduce and eventually eliminate the use of virgin plastic (newly produced plastic) in laundry detergent packaging, with targeted focus upon alternatives that meet the performance requirements of the incumbent, while reducing environmental and health hazards. This challenge comes from our partner organization ECOS, whose mission is to create eco-conscious cleaning products that are sustainable and affordable.

Dominating the packaging industry, high-density polyethylene (HDPE) and polyethylene terephthalate (PETE) are the most prevalent packaging materials for liquid laundry detergent. Following industry standards, ECOS uses PETE for smaller products and HDPE for large products (above 70 fl oz). ECOS is an industry leader in sustainable packaging using approximately 25% of post-consumer recycled (PCR) plastic in their packaging . Since PETE and HDPE both have established recycling programs, it is easier to incorporate PCR PETE and HDPE than PCR from a newer and less common plastic like PLA. Additionally, PCR plastic content reduces the quality of the packaging, keeping alive the demand for virgin plastics (Muringayil Joseph et al., 2024; Jiang & Bateer, 2025). Despite industry's recent push for alternatives, HDPE and PETE are hard to replace due to their excellent mechanical and chemical properties and established economies of scale. HDPE and PETE both have high strength and stiffness (Poly PVC, n.d.; Neelalochana et al., 2025). Most importantly, these materials both provide excellent moisture barriers, an essential attribute in containing liquids, and one that is hard to replicate with bio-based materials. Despite these desirable technical metrics, their environmental and human health impacts highlight the need to invest in alternative plastics. HDPE and PETE create several environmental and health concerns, including non-renewable petrochemical feedstock which contain toxic additives as well as the creation of microplastics that persist in the environment and cause health issues in people and animals (Belmaker et al., 2024). These challenges motivate the usage of alternative materials that reduce reliance on virgin plastics without compromising performance.

2.2 Approach and Methodology

Based on the challenge set forth by ECOS we identified eight core criteria for assessing alternatives (Fig I). The key performance categories include structural properties (resist deformation), barrier properties (prevent leakage), and thermal properties (withstand temperature fluctuations during transport). Also, while we were asked to propose alternatives that are chemically compatible with the detergent, we were later assured that the formulation is stable and to disregard this point. Also, aligned with ECOS's mission and vision, the materials should be of vegan origin and reduce virgin plastic use. Our partner stipulated that the packaging must be compatible with existing closures (i.e. caps, pumps) still made from incumbent plastic. Critically, our alternatives must reduce human health and environmental hazards.

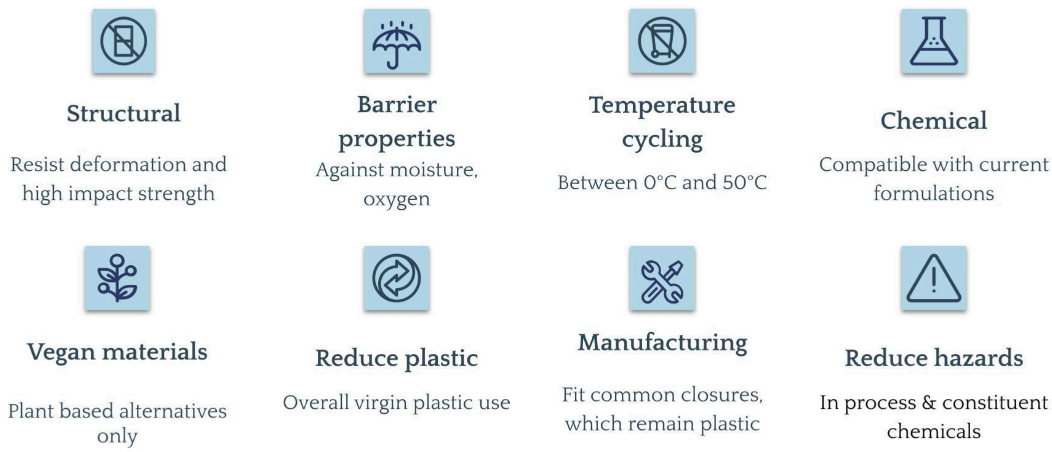

Fig I. General core criteria used to assess alternative solutions.

2.2.1 Technical performance methodology

We assessed the technical performance and the environmental health performance of each alternative relative to the incumbent material. For technical performance, there are several measurements and properties that are necessary for the packaging to be compatible with liquid laundry detergent. Those can be divided into 3 categories:

a) The mechanical properties focus on the material's abilities to withstand different forces. Impact strength is the ability to withstand sudden, forceful impacts without breaking (Instron, n.d.); tensile strength is the threshold at which further stress leads to disproportionate deformation (Horwood & Chockalingam, 2023); and elongation at break is a measure of a material's ability to resist changes in shape without cracking (Special Chem, 2025).
b) On the other hand, the barrier properties focus on keeping oxygen and water from interacting with the packaged product. Oxygen permeability measures how easily oxygen passes through a material. Oxygen transmission rate (OTR) is the permeability relative to the thickness of the material (*ScienceDirect Definition*, 2024); and water vapor transition rate (WVTR) is a standard industry measurement that measures how much water vapor passes through a material over time, with a lover value indicating better moisture barrier properties (Basha et al., 2011).
c) Lastly, for the heat properties we look at melting temperature, which is the temperature at which a material changes states from solid to liquid (Enformak, 2025).

Because minimum performance thresholds for alternative materials in detergent packaging have not been formally established, we benchmark candidate materials against the properties of the incumbent packaging material, HDPE (shown in Table I). Specifically, we use HDPE's values, the top row of table I, because HDPE is widely used for large laundry detergent containers. The reference material, through its extensive commercial use, demonstrates mechanical and barrier properties suitable for this application.

Substantial disparities in the technical properties of incumbent plastics further suggest that the functional requirements for detergent packaging do not require simultaneous optimization across all performance metrics. For example, PETE's tensile strength is 3 times that of HDPE while HDPE's oxygen permeability is 22 times that of PETE. These differences arise in part from experimental and testing variation, but more fundamentally reflect that these polymers were engineered to prioritize different performance characteristics while remaining suitable for comparable packaging applications.

Overall, the effective use of these two materials with notably different property profiles supports our inference that HDPE's properties likely represent conservative upper bounds rather than strict minimum functional requirements. As such, we use HDPE as a screening benchmark to evaluate alternative materials, recognizing that materials with properties below HDPE may still be functionally acceptable in practice.

Table I. Range of acceptable values for the technical properties of the incumbent plastics.

	Mechanical Properties				**Barrier Properties**		**Heat Properties**
	Tensile Strength	Elongation at Break	Impact strength	Elastic Modulus	WVTR[4]	OTR[4]	Melting Temperature[5]
Units	MPa	%	kJ/m2	MPa	g / m2 day (85% RH)	ml/ m2 bar day (85% RH)	°C
HDPE	18 - 20 [1]	≥ 380 [3]	31 [3]	800 - 1000 [3]	7.75	703	120 - 140
PETE	55 - 75 [2]	≥ 50 [2]	3.6 [2]	> 2000 [2]	6.9	31	240 - 270

Sources:
1 Amjadi & Fatemi, 2020
2 SiNDA, 2025
3 MatWeb, 2010
4 De Beukelaer et al., 2022
5 Professional Plastics, n.d.

As described above, we evaluate the technical performance of our alternative strategies relative to HDPE and apply a tiered framework (Table II) to facilitate comparisons. In this table, green indicates performance comparable to or exceeding HDPE (≥ 100%), yellow indicates moderately lower performance (~50–99%), and red indicates substantially lower performance (< 50%).

This approach does not assume that HDPE defines the minimum functional requirements for ECOS detergent packaging. Rather, HDPE is used as a conservative reference point, allowing for benchmark comparisons across materials while also acknowledging that values below HDPE may still meet practical packaging requirements.

Table II. Qualitative benchmarking of mechanical, barrier, and heat properties based on HDPE performance

	Mechanical Properties				**Barrier Properties**		**Heat Properties**
% of HDPE Performance	Tensile Strength MPa	Elongation at Break (%)	Impact strength kJ/m²	Elastic Modulus MPa	WVTR g/m² day	OTR ml/m² bar day (85% RH)	Melting Temperature °C
≥ 100% *Good*	≥ 15 - 20	≥ 380	31	800 - 1000	< 7.75	< 703	120 - 140
~50–99% *Okay*	7.5 - 15	190-380	5 to 30	400-800	7.75 - 12	705 - 1000	50 - 110
<50% *Bad*	< 7.5	< 190	< 5	< 400	> 12	> 1000	Less than 50

2.2.2 Health and environmental assessment

We judged the environmental and health hazards for incumbent and alternative materials based on the constituent chemistries of the material and of the manufacturing process. First, we used Pharos and the EPA CompTox dashboard to find what authoritative lists the chemicals may be on (i.e. International Agency for Research on Cancer (IARC))(*Pharos*, n.d.; *ToxFMD Screened Chemistry™ Library - FMD*, n.d.). Next, we looked through peer reviewed literature for toxicology studies from scientific databases and the Tox Screened Chemistry Library from ToxServices; this library compiles studies for chemicals and performs complete GreenScreen assessments. From the toxicity data in the studies, we assigned chemicals a hazard level from low to high, following the GreenScreen method(*GreenScreen Method | Assess Chemicals*, 2023). Lastly, we estimated hazards for data gaps using predictive toxicology sources like EPA's GenRA and chemical intuition(*GenRA*, n.d.). After this multi-level search, missing information was denoted as a data gap.

We grouped hazards into four main categories based on the GreenScreen method. Two categories address human health issues: group I and group II human endpoints (Fig II). When assessing alternatives, we first looked for strategies that were biodegradable, compostable, or completely recyclable. Next, we narrowed down alternatives by reducing group I human health endpoint hazards. After that, we focused on reducing Group II human hazard traits like systemic toxicity and neurotoxicity. Lastly, we looked to reduce skin irritation and sensitization, eye irritation and sensitization, and respiratory sensitization. We considered these group II endpoints during the final evaluation because there are exposure mitigation techniques available like personal protective equipment (PPE) and workplace regulations that may reduce these hazards, as opposed to those addressed earlier in our process. Additionally, changing manufacturing processes to reduce human contact and airborne particulate matter can address these issues.

Fig II. Groups of hazard assessment and what hazards fell under each.

Group 1 Human Endpoints			Group II and II* Human Endpoints			Ecotoxicity	Fate	Physical Hazards
Carcinogenicity & Mutagenicity	Developmental and Reproductive Toxicity	Endocrine Activity	Systemic Toxicity	Neurotoxicity	Skin, Eye and Respiratory Irritation and Sensitization	Aquatic Toxicity Acute & Chronic	Persistence and Bioaccumulation	Reactivity, flammability, PChem traits

For the hazard assessment, we followed a similar spectrum scheme where green represents low hazards, yellow represents moderate hazards, and red represents high hazards (table III). Grey squares represent data gaps.

Table III. Color codes of hazards, from very low (dark green) to very high (dark red)

very low	low	low to moderate	moderate	moderate to high	high	high to very high	very high	data gap
VL	L	L -M	M	M- H	H	H - VH	VH	DG

2.3 Inspiration

Because detergent bottles need to be strong, resistant to water and oxygen, and withstand significant temperature fluctuations, identifying a single material that satisfies all technical requirements and also provides a substantially improved end-of-life pathway like being biodegradable or compostable is difficult. To address this we looked to commercial products that utilize layers to achieve adequate technical performance. Our approach was informed by companies like Dr. Bronner's who produce cartons with different layers to address different properties (Dr. Bronner's, n.d.). While these products offer valuable conceptual grounding, their difficult recyclability due to not being able to separate the layers to properly dispose of each material, potential material hazards, and lack of a rigid structure for large-format detergent containers highlight the need for novel alternatives.

For this separate base-coating strategy, the base provides structure and mechanical properties and the coatings provide the barrier properties. Some strategies may benefit from a third layer of fillers that also contribute to the strength. We looked for new materials for our layers to reduce hazards from traditional carton materials. For example, milk cartons have an aluminum layer that helps with strength and barrier properties, but makes cartons harder to recycle and not compostable (Gritsch et al., 2025). Additionally, we need materials that will be suited for larger packaging, meaning materials with sufficient mechanical properties. This includes, high impact strength, tensile strength, and elongation at break, as stated previously. In our case, larger packaging is based on large laundry detergent bottles, which are usually 100 oz, or 3 liters.

We considered solutions that could integrate with existing closures used in the bottles for specialized caps and pumps, assessing compatibility based on reported mechanical properties and fabrication capabilities (i.e. injection moulding)

2.4 Hazards of PETE and HDPE

The hazards of polymers do not come from the polymers themselves because polymers are generally too big to enter cells and cause harm. Instead, hazards come from monomers and oligomers that did not finish polymerizing and from other additives used in the manufacturing process. For example, HDPE and PETE come from petrochemicals and contain toxic additives such as phthalates and bisphenols, which can migrate out of materials and cause endocrine and developmental effects (Belmaker et al., 2024). These chemicals are added for durability of packaging, but the properties that assist in durability also create toxicity when people are exposed to them.

During production, there are sensitization and irritation hazards from the microplastics and fumes released during the manufacturing process (Quebec CSST-Asthma Agents). Employees of manufacturing and recycling plants face significantly higher risks, as their prolonged exposure to plastic production and handling heightens their chances of respiratory inflammation and lung cancer (Vasse & Melgert, 2024). Microplastics are produced again at the end of the plastic lifecycle during recycling and trash production. Microplastics pose a variety of hazards towards humans, including but not limited to DNA damage, metabolic disorder, immune responses, reproductive and developmental toxicity, and neurotoxicity (Li et al., 2023). Furthermore, microplastics in the environment can be ingested by aquatic organisms and other animals, which not only poses a hazard to the animal's health, but to the humans that consume them. While more research is necessary to know the extent to which microplastics affect our ecosystem and bodies, it is clear exposure leads to disorders, and potential chronic diseases.

This presents an environmental justice issue, because low-income families and communities of color are more likely to live near waste sites and manufacturing and recycling facilities due to historical redlining. These communities are disproportionately exposed to microplastic particles and volatile chemicals such as ethylene and butylated hydroxytoluene, which are used in the plastic manufacturing process as a monomer and antioxidant respectively. These residues and additives have been linked to pulmonary inflammation and oxidative stress in animal models (Muhammad et al., 2025). Children are also a vulnerable population; they are prone to microplastic inhalation and ingestion because they are closer to the ground, breathe at faster rates, and have higher rates of hand-to-mouth contact. Furthermore, America sends over 1 million tons of its plastic waste to underdeveloped countries each year, disproportionately exposing communities abroad to microplastics and their associated health hazards as environmental contamination (McCormick et al., 2019). Without proper infrastructure and information on disposal of the large volume of plastic in these developing countries, many countries resort to open burning of plastics which increases risk of heart disease, respiratory illness, and neurological disorders in residents (Pathak et al., n.d.). These environmental justice issues further stress the importance of switching to safer alternatives to plastic packaging.

In addition to human exposures, a majority of laundry detergent bottles end up in landfills and persist in the environment, creating ecological hazards (*The Dirty Little Secret of Getting Your Laundry Clean*, n.d.). Once in the environment, HDPE and PET fragments accumulate in soil, sediments, and water. Birds and turtles are especially vulnerable to ingesting polyethylene microplastics and face issues with gut health and nutrient absorption, as high levels of microplastic consumption can lead to intestinal blockage (Schuyler et al., 2014; Kühn & Franeker, 2020). Additionally, microplastics adsorb persistent organic pollutants such as PCBs and PAHs, which can bioaccumulate in marine animals, causing liver toxicity, endocrine disruption, and reducing fish reproduction (Rochman et al., 2013). As the pollutants continue to travel up the food chain, they can also bioaccumulate and biomagnify to cause problems in humans (Nihart et al., 2025).

While consumers are only minimally exposed to the monomers of HDPE and PETE and their additives, these chemicals are occupational hazards during manufacturing and environmental hazards after leaching into the environment from landfills. These hazards are displayed in the hazard table below (table IV). We chose one of the most common chemicals for each category of additive, but different manufactures may use different additives. To call out notable hazards, several of the monomers and additives have high human hazards in regards to carcinogenicity, mutagenicity, systemic toxicity. Specifically, the additives are very persistent in the environment. Since additives are not covalently bound to the polymers, they can leach into the environment, contaminate water, soil, and air (Maddela et al., 2023). The majority of the chemicals that compose the plastics exhibit low bioaccumulation, however certain manufacturing additives, including benzophenone, can accumulate in aquatic organisms and potentially affect other wildlife and humans through the food chain. In addition, once polymerized into a bulk material, plastics do not degrade and are persistent (McCormick et al., 2019; Pathak et al., n.d.; Rochman et al., 2013).

Table IV. Hazard assessment for existing chemicals

Chemical	Group 1 Human Endpoints			Group II and II* Human Endpoints			Ecotoxicity	Fate	Physical Hazards
	Carcinogenicity & Mutagenicity	Developmental & Reproductive Toxicity	Endocrine Activity	Systemic Toxicity	Neurotoxicity	Skin, Eye and Respiratory Irritation and Sensitization	Aquatic Toxicity Acute & Chronic	Persistence & Bioaccumulation	Reactivity, flammability, PChem traits
Ethylene (HDPE monomer)	M	L	DG	M	M - H	L	M	L VL	H
PTA (PETE monomer)	M	M	M	L	L - M	L (skin), M (eye), DG	L	VL	L - M
Ethylene glycol (PETE monomer)	DG	H	M - H	H	DG	H, L-M (resp)	VL	L	L

Benzoyl Peroxide (cross-linking agent)	L	L	L	M	L	H	H	L		L
Erucamide (slip agent)	L	L	L	L	L	L	L	L		L
Ammonium Polyphosphate (flame retardant)	L	L	L	L	L	M (skin), L (eye, resp)	L	VH	VL	L
Butylated Hydroxytoluene (antioxidant)	M	M	M - H	DG	DG	M (eye), DG	H	DG		DG
Benzophenone (UV filter)	H	M	H	H	M	L (eye,skin), DG (resp)	M - H	H - VH	H	L
Teflon PTFE Powder (nucleator)	H	L	L	H	L	L	L	VH	VL	L

3. Strategies

Taking inspiration from a combined base and coating approach exemplified in commercial carton products, we propose three novel strategies that emulate this approach. The first is a bamboo particles composite base, inspired by the monomers that make up paper, and a polylactic acid (PLA) and montmorillonite clay (MMT) coating. Second, a zein base with a cutin coating. And third a polyhydroxyalkanoate (PHA) mix that acts as both the base and coating, which does not need layers to meet the technical performance criteria. All key ingredients are plant-based. While not fully matching HDPE's mechanical properties, the lower hazards and improved end-of-life endpoints highlight the potential of these strategies to replace ECOS's current plastics. Additionally, benchmarking against HDPE allows for the possibility that alternative materials with lower mechanical and barrier performance remain functionally acceptable.

3.1 Layered Bamboo Composite and PLA-MMT coating

Following the inspiration from milk cartons to have a product consisting of a base and a coating, this strategy aims to fulfill the mechanical performance criteria with a bamboo particles base and the barrier properties with a polylactic acid (PLA) and montmorillonite clay (MMT) coating. Furthermore, the hazard assessment was characterized for the base and the coating as separate entities, looking into the molecules that make each one.

Following our inspiration we looked into paper as a possible base. Paper is made from wood or plant pulp, which in turn is mainly three polymers: hemicellulose, cellulose and lignin. Paper manufacturing is a resource-intensive process that has significant climate change impacts. Pulp production alone accounts for 62% of total energy consumption, 45% of greenhouse gas emissions, 48% of acidification potential, and 49% of eutrophication potential across the paper manufacturing process, which emits an average of 950 kg CO_2-equivalent GHGs overall (Sun et al., 2018). Paper, by itself, does not have the prerequisite mechanical properties to replace incumbent plastics. To overcome this technical limitation, we propose a paper base that is made from bamboo particles (BP), PLA and MMT (Kumar and Babu, 2023).

Bamboo particles, which contain the three main polymers used in paper, can be produced directly from bamboo chips by pretreating them with glycerol, crushing them with an extruder and milling them; a more energy efficient process with safer chemicals compared to paper (Lu et al., 2018). Additionally, the sum of hemicellulose and lignin makes up 65% of the dry mass of bamboo, making it one of the most important sources of lignocellulosic mass due to its rapid growth and potential to be used as feedstock in different applications (X. Li et al., 2015). All of these reasons make the bamboo composite a good alternative for a paper inspired base.

This strategy also utilizes PLA and montmorillonite clay. Polylactic acid is a bioplastic obtained by fermenting plant-sugars, like starch or molasses (Ramesh et al., 2020). It is known for its biodegradability, biocompatibility and good process ability. Montmorillonite is a silicate clay valued for its low cost and high strength, and is commonly used as a filler to enhance the thermal, mechanical, and physical properties of materials (Ramesh et al., 2020). The BP+PLA+MMT's biodegradability and high manufacturing potential highlight its value as an alternative to conventional plastics.

3.1.1 Technical Feasibility

The technical feasibility of this strategy separately analyzes the mechanical, barrier, and thermal properties. To fulfill the performance requirements, both the base and the coating are composites with PLA and MMT.

Notably, PLA + paper fiber + MMT show standalone potential in which the combination has sufficient barrier properties (Ramesh et al., 2020). However, further research needs to be done to solidify this relationship. Due to this uncertainty, we chose to add a coating to the composite. Table V below summarizes the strategy's mechanical and barrier properties of the base and coating, benchmarked with HDPE.

Table V. Mechanical and barrier properties of the BP + PLA + MMT base and the PLA-MMT coating

	Tensile Strength	Elongation at Break	Impact strength	Elastic Modulus	Water Vapor Transmission Rate	Oxygen Permeability	Melting Temperature
Units	MPa	%	KJ/m2	MPa	g / m2 day (85% RH)	ml/ m2 bar day (85% RH)	°C
BP + PLA + MMT	25.85	1.8	7.9	N/A			160
PLA-MMT					11	1012	150 - 180

Kumar and Babu, 2023.

3.1.1.1 Base: bamboo fibers, PLA and clay mixture

Taking into account that paper on its own does not meet the mechanical requirements, the base for our detergent bottles would be a biopolymer hybrid composite made from bamboo particles (BP), PLA and montmorillonite clay (MMT) particles. In a study by Kumar and Babu (2023), they created this material by melting the PLA in a furnace, stirring and adding the BP. After stirring for 15 minutes, the clay particles are slowly added. Finally, the melt was cast into a die and compressed with a cold press (Appendix I). Different weight percentages of the components were added for each sample they tested.

Mechanical properties

While tensile strength of the BP mixture matches HDPE's performance, the mixture still requires improvement to improve impact strength and elongation at break. According to Kumar and Babu (2023) the biopolymer composite BP+PLA+MMT shows a tensile strength within the range of HDPE when the mixture contains 10% wt of bamboo particles. The composite's tensile strength decreases if the content of bamboo particles increases due to a poor link between PLA and bamboo. To expand on the researcher's mixture, we recommend conducting tests to optimize the ratio to maximize tensile properties.

Testing for elongation at break, the composite is brittle in comparison with our incumbent plastics. When the three materials are mixed, bamboo, PLA and the clay, the elongation at break still remains under 2%, much lower than HDPE's > 380%. We recommend an addition of a stabilizer with high elasticity to improve this composite's elongation at break.

Lastly, checking the impact strength, we found on different peer reviewed articles that the different methodologies for testing greatly impact the results. Since the test depends on the size and thickness of the sample it measures, we do not have certainty that the collected data for our strategy and the current plastics were measured with the same methodology. Despite this limitation, we present the information in table VI below to relatively compare the mixture's impact strength to HDPE. While the mixture's impact strength falls below HPDE's values, it can be improved with increased wall thickness or blending with a stabilizer.

Table VI. Mechanical strength of composite of paper with bamboo, PLA and MMT

Composite mix	**Tensile strength**	**Impact strength**	**Elongation at Break**
PLA [1]	~22.5 MPa	5.1 KJ/m^2	~2.0 %
PLA + BP [1]	23.65 MPa	6.4 KJ/m^2	~1.2-1.6%
PLA + BP + MMT [1]	25.85 MPa	7.9 KJ/m^2	~1.8 %
HDPE [2]	18 - 20 MPa	31 KJ/m^2	>380 %

1 Kumar & Babu, 2023;
2 Amjadi & Fatemi, 2020.

Thermal Stability

The thermal stability of the PLA+BP+MMT mixture is sufficient, exceeding the technical requirement of withstanding temperature cycling from 0 to 50 °C. Thermal degradation, melting temperature, and glass transition temperature are all sufficiently above the upper temperature requirement of 50 °C (Kumar & Babu, 2023).

3.1.1.2 Coating: PLA-MMT composite

This coating combination of PLA biopolymer and MMT clay produces a water and oxygen barrier comparable to those of HDPE and PETE plastics. Table VII below summarizes these barrier properties for PLA-MMT. Values across papers were standardized using industry-standard units for their respective metrics. These favorable barrier properties highlight PLA-MMT's promise as a coating for a base-coating composite that can replace conventional plastics.

Water Barrier

Using 6 layers of PLA-MMT on a paper base, a water vapor transmission rate (WVTR) comparable to HDPE and better than PETE was achieved (Bandera et al., 2016; GLL, 2013). Water Vapor Permeability (WVP), another measure for moisture barrier properties, describes how readily water vapor in gaseous form can pass through a material. Across multiple papers, WVP is slightly higher than HDPE's WVP but better than PETE (Bandera et al., 2016; Svagan et al., 2012; Keller & Kouzes, 2017; Versaperm, 2014). We predict that the PLA-MMT strategy will perform suitably as a moisture barrier based on its WVTR and WVP values, which are comparable to those of HDPE and PETE.

Oxygen Barrier

PLA-MMT also has strong oxygen barrier properties that make it suitable for ECOS products. Across multiple papers examining Oxygen Permeability of PLA-MMT, the values were comparable to that of HDPE and better than PETE (CP Lab Safety).

The combination of strong moisture and oxygen barrier properties make PLA-MMT a promising coating for paper. Notably, the studies used to evaluate the coating's properties differ by types of layers, number of layers, layer thickness, bottle size and volume tested, and temperature and vapor pressure. While measurement variations exist, the consistently positive outcomes across comparable studies confirm PLA–MMT as an effective alternative to HDPE and PETE for moisture and oxygen barrier applications.

A summary of all the barrier properties of PLA-MMT mixtures compared to HDPE and PETE is shown in **table VII**. It is important to consider that the values are impacted by bottle size/volume, number of layers, types of layers, layer thickness, temperature, and vapor pressure. The measurements give a good idea of where each composite stands within that category, but it is not accurate to compare the measurements directly with one another. It should be more qualitative.

Table VII. Summary of water barrier and oxygen barrier properties of PLA-MMT mixtures compared to HDPE and PETE.

Barrier	**PLA-MMT** [1]	**PLA-MMT + Chitosan** [2]	**PLA-MMT + PEI + Nafion*** [3]	**HPDE** [4,5,6]
WVTR **g/(m^2day)**	11			7.75
WVP **g·mm/(m^2day·kPa)**	0.665	0.90±0.024		0.1-0.24
OP **(mL·mm/(m^2·day·kPa)**		0.255×10^{-2}	0.50	0.719

** Nafion is a perfluorosulfonic acid polymer, a type of PFAS. Its inclusion in this table was used to demonstrate PLA-MMT's oxygen barrier properties, not serve as a recommendation for its inclusion in the PLA-MMT coating.

1 Bandera et al., 2016
2 Svagan et al., 2012
3 Zhu et al., 2025
4 GLL, 2013
5 Keller & Kouzes, 2017
6 CP Lab Safety

Chemical Compatibility

Both PLA and MMT would comply with the goal pH compatibility range of 3-10. Notably, the performance and stability of the PLA–MMT nanocomposite are influenced by environmental pH conditions. PLA contains hydrolytically degradable aliphatic ester bonds that are particularly susceptible to nucleophilic attack by hydroxide ions. As a result, hydrolysis of PLA is highly accelerated under strongly basic conditions (pH ≥10), leading to chain scission and the formation of lactic acid, carbon dioxide, and water (Mitsutaka et al., 2023). This degradation pathway is thermodynamically favored in alkaline environments and can significantly shorten the material's service life in high-pH applications. Conversely, at neutral or mildly acidic pH levels, PLA remains relatively stable, preserving its mechanical integrity and barrier performance. MMT clay, the nanofiller in the composite, exhibits sensitivity to both extremely acidic and basic environments as well (Altin et al., 1999). Under such conditions, the layered silicate structure may undergo ion exchange or partial dissolution, altering the interlayer spacing and potentially compromising reinforcement effectiveness. However, within moderate pH ranges, MMT maintains its structural integrity and continues to contribute to the composite's mechanical and barrier properties.

An important factor in maintaining the barrier performance of PLA–MMT composites is the type and interactions of cations within the MMT layers. Because sodium ions possess a larger hydration radius and lower charge density than calcium ions, Na–MMT undergoes greater interlayer hydration and exfoliation within the PLA matrix. This improved dispersion increases diffusion path tortuosity, resulting in higher resistance to water permeation relative to Ca–MMT (Yan et al., 2021). These cation-dependent interactions influence both the degree of clay dispersion and the nanocomposite's final properties. Sodium-exchanged MMT will last longer and maintain better oxygen and water barrier properties, even when exposed to moderate variations in environmental pH.

Technical Conclusion

In conclusion, the combination of a PLA-BP-MMT composite as a base and the PLA-MMT layers of coating create a product that satisfies key mechanical and barrier requirements of ECOS packaging. The composite's high tensile strength makes it suitable for mechanical stresses associated with the manufacturing and distribution of the product. Furthermore, the PLA-MMT coating adds water and oxygen barrier properties comparable to that of conventional plastics, conferring barrier properties necessary for ECOS's liquid products. Increased base thickness, mixture with a stabilizer, and field testing should be performed to assess the composite's true impact strength and ductility. These results demonstrate that a PLA–BP–MMT composite with PLA–MMT layering is a strong and viable alternative to conventional plastic packaging.

3.1.2 Hazard Assessment

To evaluate the health, environmental and physical hazards associated with the paper-based packaging strategy, a comparative hazard assessment was conducted across key human-health endpoints, ecotoxicity, environmental fate, and physical hazards for the primary materials and relevant constituents. Table VIII summarizes the hazard classifications for hemicellulose and lignin-based paper, associated monolignols, mineral fillers, and polymer coatings, highlighting where potential risks arise and remaining data gaps.

Table VIII. Hazard assessment for Paper shows predominantly low toxicity and environmental persistence, but data gaps stem from sourcing methods.

	Group 1 Human Endpoints			Group II and II* Human Endpoints			Ecotoxicity	Fate		Physical Hazards
Chemical	Carcinogenicity & Mutagenicity	Developmental and Reproductive Toxicity	Endocrine Activity	Systemic Toxicity	Neurotoxicity	Skin, Eye and Respiratory Irritation and Sensitization	Aquatic Toxicity Acute & Chronic	Persistence and Bioaccumulation		Reactivity, flammability, PChem traits
Hemicellulose	L	DG	DG	DG	DG	L-M (resp)	DG	DG	VL	M (flammability)
Lignin (polymer)	DG	DG	DG	DG	DG	L-M (resp)	DG	L-M (takes months)	L	M (flammability)
Coniferyl alcohol	DG	M*	DG	DG	DG	DG	DG	DG, likely biodegradable	L	L

Sinapyl alcohol	L*	M*	DG	DG	DG	H (skin, eyes)	DG	DG, likely biodegradable	L	L
p-coumaryl alcohol	DG	DG	DG	DG	DG	L (skin, eyes)	DG	DG, likely biodegradable	L	L
Bentonite / Montmorillonite	DG	DG	DG	L	DG	DG, H (resp)	DG	H	DG	DG
PLA polymer	DG	M	M	M	H	M	H	L	H	Biodegradable, hydrolizable
Lactic acid	L	L	L	L	M	H (skin, eye), M (resp)	L	L	L	Weak acid, metal corrosive
Polybutylene adipate-co-butylene terephthalate (PBAT)	L	M	M	H	H	M	H	L	L	Slowly hydrolyzes

3.1.2.1 Paper

The paper-based strategy is a significant improvement in safety and environmental performance compared to existing packaging materials such as HDPE and PETE. Paper is composed of naturally occurring biopolymers, such as hemicellulose and lignin, which are derived from renewable and consumable plant biomass such as bamboo, wood, or other agricultural waste. As a result, the material does not bioaccumulate, minimizes persistent microplastic formation, is fully biodegradable under aerobic conditions, and can be reintegrated into soil (Kadac Czapska et al., 2023). The paper strategy also eliminates exposure to several chemical additives common in plastic packaging.

Life-cycle analyses demonstrate that switching from virgin plastic use for paper can significantly reduce greenhouse gas emissions, depending on how the fiber is sourced and energy inputs (Savi, 2023). Paper is also generally compatible with recycling and composting streams, eliminating the need for incineration that emits toxic air emissions in plastic waste management. Before large-scale implementation, however, occupational hazards must be considered. In the papermaking process, worker exposure to feedstock dust, including bamboo and other lignin fibers, poses a respiratory hazard. Chronic inhalation of airborne particles in paper manufacturing is associated with bronchitis and nasal cancer (Inchem, 1997). Regular air monitoring, dust suppression systems, and proper ventilation are essential to mitigating some of the hazards from this exposure. Compared to conventional wood pulping, bamboo-based paper production often relies on high-yield mechanical processes that retain hemicellulose and lignin, reducing the need for harsher chemical treatments and lowering overall chemical burden (Hawanis et al., 2024). Additionally, the use of greener fillers further improves the hazard profile of this strategy. Agricultural residues such as pineapple leaves or other plant waste can be incorporated as fillers or fiber sources, reducing dependence on mineral fillers and synthetic additives that may contain heavy metals or generate respirable dust (Daochalermwong et al., 2020). These plant-based fillers are renewable, biodegradable, and typically lower in toxicity, while also valorizing agricultural waste streams that would otherwise be burned or landfilled.

Hemicellulose and lignin exhibit low toxicity and limited bioavailability (Jagels, 1985). Lignin's monolignols (coniferyl, synapyl, and p-coumaryl alcohol) show moderate developmental toxicity when isolated in laboratory assays, but these monomers are not expected to be released under manufacturing or end-use conditions. The overall hazard classification for these natural macromolecules is low concern for toxicity, but the material is known to be flammable (Wang et al., 2021). Concerns also come from feedstock residues from the plant fillers, rather than the paper fibers themselves. Agricultural or recycled paper sources can contain pesticide residues, PFAS from grease-proof coatings, and heavy metals from printing inks (Deshwal et al., 2019). Supplier certification, residue testing, switching to soy or vegetable-based inks, and strict sourcing from PFAS-free and sustainable suppliers mitigate these risks. Although papermaking is water and energy-intensive, its life-cycle greenhouse gas emissions remain substantially lower than those of virgin plastic production or plastic recycling (Powers, 2025). Sustainable bamboo sourcing or agricultural-waste feedstocks and closed-loop water recovery systems can reduce these environmental impacts.

3.1.2.2 PLA-MMT Coating

The composite of PLA-MMT significantly improves upon the safety of existing packaging materials. Compared to HDPE and PETE, which are petroleum-based plastics with toxic additives, PLA is biomass-sourced and is biodegradable under industrial composting conditions (Filamentive, 2025). The incorporation of small quantities of MMT clay, non-bioaccumulative, enhances barrier and mechanical performance, without introducing significant new chemical hazards.

Specifically, PLA is derived from the fermentation of plant sugars, such as corn, to form lactic acid. The monomer is then polymerized through a polycondensation or ring-opening reaction. PLA has a large molecular size, meaning it is not biologically available in its solid form which minimizes risks of dermal or inhalation toxicity. However, during its industrial synthesis, initiators such as di(trimethylol propane) and catalysts like stannous octoate are used, which are moderate reproductive and developmental toxicants (Alfa, 2025). Therefore, worker exposure to these substances pose an occupational hazard and should be mitigated with closed reactor systems, ventilation, and PPE, such as chemical resistant gloves, safety goggles & face shields, and lab coats, to prevent inhalation and dermal contact. Furthermore, PLA needs very specific conditions to break down and is only biodegradable under industrial composting conditions. In terms of hazards, PLA is considered a biodegradable plastic, but it can suffer photaging if exposed to UV light, causing a polymer chain scission which is a process that produces shorter PLA oligomers, lactide, and free lactic acid, rather than complete biodegradation (Li et al., 2024). These fragments increase surface embrittlement and promote physical fragmentation of the material into microplastic particles, which persist abundantly in aquatic and terrestrial environments and can cause oxidative damage and neurobehavioral changes in aquatic species including altered feeding behavior, stress, and locomotion (Xiao et al., 2024). These findings explain why PLA shows high concern for neurotoxicity and aquatic toxicity in Table VIII despite low intrinsic chemical toxicity. The monomer, lactic acid, exhibits low hazards for Group I endpoints but can cause skin irritation (Pharos) and respiratory irritation if its vapor is inhaled (NOAA, 1999).

The addition of montmorillonite (MMT) nanoclay reinforces mechanical and barrier properties, allowing thinner packaging layers and lower material use. MMT is a naturally occurring silicate mineral with low intrinsic toxicity and no evidence of bioaccumulation in humans or wildlife (Wang, 2024). During industrial processing, airborne exposure to MMT nanoparticles can occur if powders are handled in open systems which can potentially cause respiratory irritation or inflammation. Therefore, local exhaust ventilation and sealed mixing equipment are recommended to prevent inhalation. Once MMT is fully embedded within the PLA matrix, release potential is minimal, and leaching under normal use conditions is unlikely. Overall, MMT has low hazards, and the main source of concern would be due to accidental inhalation during processing.

From an environmental justice perspective, PLA–MMT production and end-of-life processing are less geographically concentrated in low-income or marginalized communities compared to petrochemical refineries and incineration facilities. However, the agricultural sourcing of PLA feedstocks (e.g. corn or sugarcane) can contribute to land-use pressures, pesticide exposure, and resource competition, which disproportionately affect rural agricultural laborers in developing regions. Sustainable sourcing policies and certification programs, such as those limiting pesticide use and promoting fair labor practices, can mitigate these inequities.

Hazards Conclusion

Overall, the paper-based packaging strategy poses significantly lower hazards, rapid environmental degradability, and lower persistence and bioaccumulation than HDPE and PETE. The main health and safety concerns center on occupational dust exposure and potential feedstock contamination, both of which can be mitigated through standard industrial hygiene practices and supplier sustainability verification. In polymeric form, PLA is not readily biologically available and requires specific industrial composting conditions to biodegrade. Factors such as improper disposal and incomplete breakdown (due to UV-induced degradation, hydrolysis reactions, or mechanical degradation) can lead to microplastic formation, which has exotoxicity and bioaccumulation hazards. Montmorillonite clay exhibits low hazards, with the main concern being potential respiratory irritation from airborne particles during the manufacturing process. When sourced and managed responsibly, this paper-based strategy provides a safer, renewable alternative for ECOS packaging that aligns with their environmental health and sustainability goals.

3.2 Layered Zein and Cutin Coating

This strategy utilizes a zein base with a cutin coating to create a composite that can replace HDPE plastic. The hazard assessment for these compounds and the chemical required in their manufacturing is detailed below.

Zein is a highly biodegradable, plant-derived material that is used as a base for novel biopolymers (Plasencia et al., 2025). Zein protein is extracted from the endosperm of corn, utilizing a byproduct of corn processing. Manufacturers use zein derived from corn to create biodegradable films, edible coatings, and materials for food and medical applications (Plasencia et al., 2025). Its current use in various industries and sourcing from a highly-produced crop highlights zein's large manufacturing potential. While primarily made into packaging films, zein can be also made into a rigid biopolymer resin. We employ this specific application of zein for the base component of this strategy.

Cutin is a core structural component of the cuticle in plants, providing barrier properties and preventing water loss (Chen et al., 2011). This waxy, insoluble layer can be found on the leaves, stems, and fruits of plants. In addition to preventing water loss, the cuticle plays critical roles in UV blocking, gas exchange (Polisetti et al., 2024). Cutin is a structural matrix of fatty acid chains and saturated and unsaturated fatty acids that are cross-linked with glycerol. Notably, cutin is highly biodegradable, breaking down in soil in 3-8 months and exhibiting a higher degradation rate than polylactic acid (PLA) (Ruffini et al., 2024). Cutin can also be derived from plant waste. One potential integration is the extraction of cutin from byproducts of the tomato industry. Tomatoes are the second most produced and consumed vegetable world-wide and up to 30% of tomato pomace (leftover plant material) is lost as food waste. Cutin makes up a large proportion of tomato pomace, highlighting a large amount of raw cutting material than can be potentially utilized. Notably, there is high variance in cutin's water barrier properties depending on the plant species the cutin is isolated from (Polisetti et al., 2024). Further research should explore these differences and identify which plant has the combination of strong barrier properties and sourcing feasibility. Tomatoes are a promising source of cutin because of their large feedstock availability, high pomace proportion, and robust barrier properties.

Cutin's biodegradability and high manufacturing potential highlight its value as an alternative to conventional plastic coatings.

3.2.1 Technical Feasibility

Zein and cutin's mechanical and barrier properties provide promising but imperfect results when compared to HDPE plastics. A summary table highlighting key properties is shown in table IX below.

Table IX. Mechanical and barrier properties of the Zein base and the Cutin coating

	Tensile Strength	Elongation at Break	Impact strength	Elastic Modulus	Water Vapor Transmission Rate	Oxygen Permeability	Melting Temperature
Units	MPa	%	kJ/m2	MPa	g / m2 day (85% RH)	ml/ m2 bar day (85% RH)	°C
Zein mixture[1]	22	6.8	2.4	479			N/A *
Cutin mixture[2]					8.8		76.5
Cutin[3]						165 - 736**	

[1] Zein mixture containing 15% glycerol, 10% urea

[2] Cutin Mixture 1 of (HDDA:HHA) + Glycerol

[3] Cutin derived from plant cuticles (citrus, pepper, tomato)

* Zein does not have a defined melting point; it degrades before melting

** At 100% RH

3.2.1.1 Base: Zein

The zein composite is made up of three core components: zein, urea, and glycerol. Glycerol is a commonly used protein plasticizer and cross-linker that reduces material brittleness through the formation of hydrogen bonds (Plasencia et al., 2025). Its addition allows for extrusion and injection molding. Urea is a denaturing agent that breaks down proteins through hydrogen bonding with water molecules that surround the protein. Regarding manufacturing of the composite, commercially purchased zein powder is mixed with glycerol and urea in an extruder and then injection-moulded under high heat and pressure to form the thermoplastic resin. All zein mixtures exhibited good biodegradability with >80% mass loss after a few months (Plasencia et al., 2025).

Mechanical Properties

The authors tested various mixtures of the zein composite, comparing the tensile strength, elastic modulus, impact strength, and elongation at break for mechanical properties (Plasencia et al., 2025). Multiple mixtures achieved tensile strength at or near HDPE's values, suggesting that the mixture has strong mechanical properties. The zein mixtures have an elastic modulus around half of what typical HDPE bottles have, suggesting a more flexible composite material. Impact strength and elongation at break are well below the HDPE incumbent, requiring structural workarounds or fillers to improve their properties. Additionally, lower urea content increases elongation at break of the zein composite.

Two of the most promising mixtures are highlighted in Table X below. A combination of Zein, 15% glycerol, and 10% Urea is the best overall. It has the highest tensile strength (σmax) of the mixtures while keeping moderate stiffness and some ductility. Tensile strength is the most important number for thin-wall structural parts, and this sample is the closest to typical bottle-grade strengths and thus the most promising candidate mechanically. Notably, the modulus is lower than HDPE and elongation and impact are low. This mixture may require thicker walls or reinforcement.

Another promising zein formulation includes 20% glycerol and 5% urea. This mixture has the best combination of higher elongation and highest impact strength of the group while retaining good tensile strength. While impact strength and elongation at break are higher than the first mixture, its values still fall below those of HDPE.

Design and manufacturing of zein bottles that are appropriate for ECOS products can help address some of these mechanical strength concerns. Increasing wall thickness of the zein composite and structural ribbing and reinforcement around key stress points can increase the bottle's elastic modulus and impact strength. Further modifications of the zein formula and potential additions of fillers can improve the elastic modulus of the mixture.

Table X. Mechanical strength of composite of paper with bamboo, PLA and MMT

Sample	**Tensile Strength (σmax, MPa)**	**Elastic Modulus (MPa)**	**Impact strength (kJ/m2)**	**Elongation at break (%)**
Zein + 15% glycerol + 10% urea [1]	21.3 ± 2.8	479 ± 3	2.4 ± 0.3	6.8 ± 0.7
Zein + 20% glycerol + 5% urea [1]	18.4 ± 1.4	455 ± 6	3.1 ± 0.1	9.1 ± 0.8
HDPE [2]	18 - 20 MPa	800-1000	31 KJ/m^2	>380 %

1 Plasencia et al., 2025
2 De Beukelaer et al., 2022.

Thermal Stability

The thermal stability of the zein mixture is sufficient, exceeding the technical requirement of withstanding temperature cycling from 0 to 50 °C. Thermal degradation is significantly above the upper temperature requirement of 50 °C. The zein mixture does exhibit a low glass transition temperature where the material starts to soften in the temperature range of 50-80 °C, but the material remains stable in most temperature scenarios. Zein has a melting point of around 266-283 °C but degrades before it melts (Wei et al., 2019).

3.2.1.2 Coating: Cutin

The specific cutin coating we recommend is a synthetic cutin mimic that utilizes the same building blocks as natural cutin. It consists of two hydroxy fatty acid chains—Hexadecanedoic

Acid (HDDA) and Hydroxylhexadecanoic Acid (HHA)—which are bound together by glycerol to form a heterogenous structure (Polisetti et al., 2024). Extraction of natural cutin is resource-intensive, requiring a large amount of organic solvents. In contrast, synthetic production of cutin is less resource-intensive and takes out the added complications of sourcing and establishing economies of scale for natural cutin.

The cutin formulation is created through a melt polycondensation process at 180°C for 8 hours. Dibutylin oxide, a catalyst used in organic synthesis, is added as a dry ingredient with HDDA and HHA initially. The resulting mixture is subsequently processed with chloroform and methanol and solvent-casted and compression-molded to make films. The resulting films have a thickness of 74 ± 8 µm.

Water barrier

Water vapor transmission rate (WVTR) was measured at 23 °C and a relative humidity gradient of 0 to 50%. The (HDDA:HHA):Glycerol composite exhibited a WVTR comparable to that of HDPE and better than just HDDA and Glycerol. Notably, both cutin films exhibited much better WVTRs than another popular biopolymer, chitosan. Specific values are detailed below in table XI.

Table XI. Water Vapor Transmission Rates of various compounds

Compound(s)	**WVTR** (g/m^2day, 23 °C, 0-50% RH)
HDDA + Glycerol [1]	13.5 ± 2.0
HDDA+ HHA + Gly [1]	8.8 ± 1.7
Chitosan [1]	176 ± 19
HDPE* [2]	7.75

Note: Values for HDDA+Gly, HDDA+HHA+Gly, and Chitosan were standardized from g µm m^{-2} day^{-1} using given film thickness of 74 ± 8 µm

* HDPE's WVTR was measured at 23 °C, 85% RH

1 Polisetti et al., 2024

2 De Beukelaer et al., 2022.

Oxygen Barrier

The synthetic cutin mimic used to ascertain water barrier properties did not report oxygen permeability (OP). Instead, we looked at natural cutin instead to examine oxygen barrier properties. Notably, research is limited that examines the oxygen permeability. A 1982 paper published in *Planta* is the only paper directly measuring OP coefficients in the scientific literature when using keyword searches of "cutin" and "oxygen permeability". Despite this clear data gap, the paper does report OP of three different plant species: *Citrus aurantium* (bitter orange), *Capsicum annuum* pericarp (common pepper), and Tomato pericarp. (Lendzian, 1982).

Cutin matrices were extracted from the leaves of these three plants using methanol and chloroform. To test OP, researchers pumped O2 gas and O2/N2 mixtures at 100% RH and 20 °C through the cutin.

All three plant cuticles exhibit very low oxygen permeability, at the same or lower than HDPE's OP. Notably, waxy (lipid-soluble) cuticles have stronger oxygen barriers and lower OPs, as highlighted by the citrus aurantium leaf cuticle with the lowest OP. These results lend credence to cutin's use as a robust oxygen barrier.

Table XII. Oxygen permeability values for three different plant species and HDPE

Species	**Oxygen Permeability** (ml/ m^2 bar day, 100% RH, 20 °C)
Citrus aurantium leaf cuticle [1]	165
Capsicum annuum pericarp cuticle [1]	767
Tomato pericarp cuticle [1]	603
HDPE* [2]	703

* HDPE's WVTR was measured at 23 °C, 85% RH
1 Lendzian, 1982
2 De Beukelaer et al., 2022.

UV Transmittance

The synthetic cutin mimic exhibited low direct UV transmittance, suggesting strong UV-barrier properties (Polisetti et al., 2024).

Technical Conclusion

In conclusion, the combination of a zein composite as a base and cutin as a coating creates a product that satisfies key mechanical and barrier requirements of ECOS packaging. Zein's high tensile strength highlights its suitability for mechanical stresses associated with the manufacturing and distribution of the product. Additionally, the cutin coating adds water and oxygen barrier properties comparable or better than that of HDPE, conferring barrier properties necessary for ECOS's liquid products. The cutin coating also offers UV-barrier properties that protect ECOS products from sun exposure. Increased base thickness, mixture with a stabilizer, and field testing should be performed to assess the composite's true impact strength and ductility. These results highlight the potential for a zein composite with cutin layering to be a viable alternative to current plastic packaging.

3.2.2 Hazard Assessment

The combination of a zein base with a cutin coating provides a safer alternative to conventional plastic packaging for ECOS. The hazard table below highlights the hazards of the polymers and monomers themselves and the chemicals used to manufacture them.

Table XIII. Hazard assessment for Zein and Cutin

	Group 1 Human Endpoints			Group II and II* Human Endpoints			Ecotoxicity	Fate		Physical Hazards
Chemical	Carcinogenicity & Mutagenicity	Developmental and Reproductive Toxicity	Endocrine Activity	Systemic Toxicity	Neurotoxicity	Skin, Eye and Respiratory Irritation and Sensitization	Aquatic Toxicity Acute & Chronic	Persistence and Bioaccumulation		Reactivity, flammability, PChem traits
Corn prolamine protein (zein)	VL	L	L	L	DG	L-M	VL	VL	L	Hydrophobic, biodegradable
Cutin *main monomer	DG	L	L	L	L	L	L	L	L	L (flammability)
Chloroform	H	H	M-H	H	M-H	H (skin, eye), M (resp)	M	L	L	L
Hexadecanedioic acid (HDDA)	L	L	DG	DG	L	M	DG	L	L	L
Hydroxyhexadecanoic acid (HHA)	DG	DG	DG	L-M	DG	L-M	L-M	L	M	L (flammability, combustibility)
Dibutyltin oxide	L-M	H	M	H	L	H(skin, resp) - VH(eye)	H	H	H	H
Methanol	L	M-H	H	L	VH	L-M (eye)	L	L	VL	L (reactivity) H (flammability)

3.2.2.1 Base: Zein

The zein-based packaging strategy improves upon safety and environmental performance compared to conventional petroleum-derived plastics such as HDPE and PETE. Zein is a plant-derived protein obtained from corn and is renewable, biodegradable, and non-persistent in the environment. In contrast to incumbent plastics that produce microplastics, zein is a naturally occurring biopolymer that does not bioaccumulate and undergoes degradation into amino acids and short peptides that are readily metabolized by soil microorganisms (Alsadat-Seyedbokaei et al., 2025). Available safety data consistently describe zein as having very low acute toxicity, carcinogenicity, mutagenicity, and low reproductive toxicity. However, comprehensive neurotoxicity data is limited (noted as a data gap in Table XIII).

The primary hazards associated with zein arise during manufacturing and processing, rather than during consumer use. Zein is often handled as a dry powder prior to incorporation into the base material, and airborne dust can cause mechanical irritation of the eyes, skin, and respiratory tract (ChemicalBook, 2025). As with other organic powders, dust accumulation may also present a combustible dust hazard under confined conditions. These hazards can be mitigated through enclosed processing systems, local exhaust ventilation, dust suppression, and appropriate personal protective equipment (Tortorella et al., 2021).

As for environmental fate, zein exhibits low persistence and high biodegradability under aerobic composting conditions. Unlike some biodegradable plastics that require tightly controlled industrial composting environments, zein degradation is enzyme-driven and does not rely on elevated temperatures or specific microbial consortia (Lin et al., 2010). As a result, zein does not persist in soil or aquatic environments and does not fragment into secondary microplastics, significantly reducing long-term environmental exposure concerns compared to HDPE and PETE. However, sourcing is a critical determinant of zein's overall hazard profile. Food-grade zein sourced from certified agricultural streams minimizes the risk of pesticide residues, heavy metals, and mycotoxins that may be present in lower-quality corn feedstocks (Tan et al., 2021). While zein production avoids many of the environmental justice concerns associated with petrochemical refining and plastic incineration, agricultural sourcing can still raise issues related to land use, pesticide exposure, and labor conditions for farmworkers (Donley et al., 2022). Sustainable sourcing practices, residue testing, and supplier certification are essential to ensuring that this zein-based packaging achieves its intended health and environmental safety goals.

3.2.2.2 Coating: Cutin

The use of cutin as a surface coating further improves the safety and environmental performance of the zein-based packaging. Traditional plastic coatings often rely on fluorinated compounds, synthetic polyesters, or acrylics that can persist in the environment and contribute to microplastic formation. In contrast, cutin is a naturally occurring plant polyester that forms the protective cuticle of fruits and leaves and is inherently biodegradable. As a bio-based polymer, cutin does not bioaccumulate and ultimately degrades into small organic molecules that can reintegrate into natural biogeochemical cycles (Ali et al., 2023).

Cutin is typically obtained from agricultural residues such as tomato peels, apple skins, or citrus waste, making it compatible with circular economy approaches and generally low in toxicity across the board as shown in Table XIII; however, comprehensive standardized toxicological datasets remain limited (Mroczkowska et al., 2024). Notably, the primary hazards come from the chemical extraction processing of cutin rather than the cutin material itself. Conventional laboratory-scale and pilot-scale extraction methods frequently use solvents such as chloroform and methanol, as well as catalysts and crosslinking agents. Particularly, chloroform, methanol, and dibutyltin oxide carry high or very high hazards, including flammability, reproductive and developmental toxicity, neurotoxicity, and respiratory irritation as shown in Table XIII. Worker exposure during extraction and processing represents the most significant health risk associated with cutin-based coatings and must be mitigated through closed systems, ventilation, solvent recovery, and use of personal protective equipment (Tortorella et al., 2021). Additionally, safer extraction and processing pathways using lower-hazard alternatives like ethanol-based solvent systems can significantly reduce utilization of hazardous solvents and catalysts while preserving the functional properties of cutin coatings (Cao et al., 2025). The scalability and consistency, however, of these greener extraction methods require further research. Assumptions of safety should not be made without residue testing and process verification. Data on carcinogenicity and mutagenicity are limited and variable, representing an area where additional testing would be required for comprehensive environmental assessment. Otherwise, cutin is a promising alternative that is biodegradable under aerobic soil and composting conditions, and are not known to be environmentally toxic or pose microplastic risk (Heredia-Guerrero et al., 2017).

Furthermore, sourcing plays a central role in determining the hazard profile of this cutin coating strategy. Agricultural residues may contain pesticide or fungicide residues depending on cultivation practices, and these contaminants pose additional concerns for consumer contact (USDA, 2012). Therefore, strict supplier certification, residue screening, preference for low-input or food-grade agricultural waste streams, and greener extraction practices are critical to ensuring a low-hazard final material.

Hazards Conclusion

The combined strategy of zein as a structural base material with a cutin coating affords a fundamentally safer and more environmentally-conscious alternative to conventional plastic packaging for ECOS. The hazard assessment indicates that the primary risks come from processing steps such as powder handling or extraction rather than the finished material. These risks are mainly occupational and controllable through existing industrial hygiene practices, closed system processing, and intentional solvent and supplier selection. In contrast, many hazards associated with plastic packaging—such as chemical migration, environmental persistence, and cumulative exposure—are intrinsic to the material, making it difficult to fully address through recycling, waste management, or other downstream measures (Gupta et al., 2024). Together, the zein and cutin strategy demonstrates that effective packaging performance can be achieved without persistent plastics or toxic additives, through deliberate material selection, responsible sourcing, and precautionary design that aligns with ECOS's mission to prevent avoidable chemical hazards rather than managing them after the fact. When extracting these materials from clean feedstocks and processed using greener hazard methods, this zein-cutin strategy reduces reliance on fossil fuel-intensive supply chains and can be marketed as fully compostable, plant-derived, and microplastic-free. Further testing and research remains necessary to address data gaps related to extraction and occupational exposure.

3.3 Stand-alone PHA mix

This strategy employs polyhydroxyalkanoates (PHAs), a family of biodegradable polymers, as a biopolymer base to replace HDPE. Specifically, this section will mainly focus on polyhydroxybutyrate (PHB), which is the most commercially available polymer (it is the only polymer from PHAs family to be mass produced), integrated with glycerol as a plasticizer to improve flexibility and processibility (Koller & Mukherjee, 2022).

PHB is a polymer that bacteria naturally produce to store energy. PHB is made by fermenting renewable materials like plant sugars or agricultural waste. The polymer is compatible with the human body and is used in medical devices, food packaging, and agricultural films. Its monomer, β-hydroxybutyrate, is a natural substance in the human body. Moreover, the solid polymer does not easily enter the skin or lungs. PHB's proven safety, compatibility with human use, and successful application in a variety of products make it a promising and low risk alternative to HDPE for ECOS's packaging needs.

Adding glycerol makes PHB more flexible and easier to process into molded items, such as the laundry detergent bottles we are hoping to replace. PHB with glycerol easily breaks down in compost. While long term effects of PHB microplastics are still being studied, we hypothesize that combining PHB with glycerol is a less hazardous, biodegradable alternative to conventional virgin plastics.

3.3.1 Technical Feasibility

Unlike the previous strategies, the PHB-glycerol blend does not require a separate base and coating to achieve strong technical performance. This standalone nature offers benefits such as easier manufacturing, streamlined production, and reduced complexity, compared with the other two strategies that rely on distinct base and coating layers.

Table XIV. Mechanical and barrier properties of the PHB composite

	Tensile Strength	Elongation at Break	Impact strength	Elastic Modulus	WVTR	OTR	Melting Temp

Units	MPa	%	kJ/m2	MPa	g / m2 day	ml/ m2 bar day	°C
PHB + glycerol	20 - 40 [1]	230 [2]	20 [2]	800 - 3500 [1]	5.5 [1]	20 [1]	130 - 170 [3]

1 De Beukelaer et al., 2022
2 El-Hadi et al., 2002
3 Koller & Mukherjee, 2022

Mechanical Properties

As seen in table XIV, the technical metrics for PHA are almost as good as those for HDPE. While the alternative material does not match the incumbent plastic in elongation at break and impact strength, these properties still fall within ranges considered acceptable for industry applications. This further supports the use of HDPE as a conservative reference point, rather than a strict indicator of minimum functional requirements.

PHB on its own is a brittle material, with a 2 to 10% elongation at break (UN Climate Technology Centre & Network, 2015). The proposed blend is highly ductile at 230% elongation at break, with the ability to bend before snapping. Furthermore, based on the impact strength of 20 kJ, we expect PHB to withstand more forces than other bioplastics before damaging.

Barrier Properties

The WVTR was measured at 23°C and 85% relative humidity, providing a more than adequate barrier for a laundry detergent considering the relative humidity percentage as a high-stress condition. Additionally, the OTR, measured at 50% relative humidity, shows a high oxygen barrier that will adequately preserve the chemical stability of the detergent and maintain the integrity of any fragrance by preventing oxidative degradation.

Temperature Properties

With a melting range between 130° and 170° C, this material is suitable for typical packaging processing methods such as extrusion, injection molding, or thermoforming. Compared with HDPE, the PHB-glycerol blend exhibits a slightly broader melting range. This difference may necessitate minor adjustments in processing parameters but does not pose a significant limitation for industrial application.

Biodegradability

At the end of life, the PHB and glycerol blend will biodegrade in industrial composting or in an aqueous environment (El-Hadi et al., 2002).

Technical Conclusion

In conclusion, the PHB and glycerol blend is a viable alternative for ECOS' packaging in terms of the mechanical, barrier and heating properties. Overall, relative to HDPE, the performance metrics are comparable or modestly lower yet remain within acceptable ranges, supporting the notion that this alternative could be implemented without compromising functional performance.. PHB can be made in conventional injection-moulding processes, highlighting high manufacturing and scalability potential. The blend offers a technically feasible, environmentally-friendly packaging solution without requiring substantial changes to current production processes. Overall, this blend provides a strong balance between performance and sustainability, making it a practical alternative for ECOS' laundry detergent packaging.

3.3.2 Hazard Assesment

Table XV. Hazard Assessment of PHB composite

	Group I Human Endpoints			Group II and II* Human Endpoints			Ecotoxicity	Fate		Physical Hazards
Chemical	Carcinogenicity & Mutagenicity	Developmental and Reproductive Toxicity	Endocrine Activity	Systemic Toxicity	Neurotoxicity	Skin, Eye and Respiratory Irritation and Sensitization	Aquatic Toxicity Acute & Chronic	Persistence and Bioaccumulation		Reactivity, flammability, PChem traits
Glycerol	DG	DG	DG	DG	L	DG	DG	L	L	DG
PHA*	L	DG	M	L	L	DG	L	L	M	L

*PHA refers to PHA, PHB, and PHB monomer

PHAs are an inherently safer material, likely due to their microbial origin. Toxicological studies report no carcinogenicity in rats (Peng et al., 2011), and safety data sheets identify no major physical hazards. Additionally, PHAs present low hazards across most Group I Human Endpoints, although the developmental and reproductive hazards remain unknown.

PHB likely poses minimal risk to human health during normal handling and use. PHB has high molecular weight and inertness which prevent skin and inhalation toxicity. Furthermore, numerous biomedical applications demonstrate that PHAs do not elicit immune responses (Ang, 2020). On the other hand, occupational hazards do occur during the manufacturing process of PHAs, where workers may be exposed to organic solvents or airborne particles like PHA polymer dust. Closed processing systems, local exhaust ventilation, and appropriate personal protective equipment are required to control exposure.

Environmental hazards associated with PHB remain relatively low as PHB fully degrades within two weeks (100% RH soil), with significant reductions in mechanical properties in three days (Kim et al., 2023). Furthermore, ecotoxicological studies report no adverse effects on Daphnia manga (water flea) when PHB microplastics are ingested with food (Serra et al., 2025). However, long-term exposure to PHB nanoplastic particles has shown some negative effects, altering prey consumption behavior in aquatic organisms (Santos et al., 2024). Overall, we found ecotoxicity data for biodegradable plastics to be sparse, limiting our understanding of PHB's environmental impacts and toxicity.

Glycerol also exhibits low hazards but contains several data gaps. One important concept to note is that the human body naturally oxidizes glycerol, which prevents accumulation (Tildon, 1976). Toxicological assessments show no authoritative classification for carcinogenicity, reproductive toxicity, or sensitization, though some studies suggest potential genotoxicity in bacterial and animal models. Developmental toxicity is classified as low-to-moderate, and some sources show glycerol as causing skin and eye irritation, but this classification remains unverified (Sigma-Aldrich, 2025). Environmental data indicates glycerol biodegrades readily in soil under aerobic conditions (Raghundandan et al., 2014)). In all, glycerol is widely used in many applications and is considered low hazard due to its ready biodegradation and low human health effects.

PHA production relies on microbial fermentation of renewable carbon sources, which reduces incumbent packaging reliance on petrochemical refining and its related community exposures. Some renewable carbon sources include sugars, starches, or agricultural waste materials. However, agricultural feedstock production introduces pressures around land-use and labor risks that largely affect rural and low-income communities. Therefore, it is important to use sustainable feedstock sourcing practices, such as using crop residues and waste streams, to provide the carbon sources necessary for PHA synthesis.

Hazards Conclusion

We propose PHA and glycerol as a safer, biodegradable alternative to virgin plastics used in ECOS packaging. Potential hazards in endocrine activity and bioaccumulation should be noted. The main concern occurs in the processing step of PHA, where workers may be exposed to organic solvents or airborne PHA particles; these exposures can be controlled through employing existing worker safety practices. Unlike conventional plastics, PHB degrades rapidly and is safe in aquatic environments, though data gaps remain for long-term impacts. Overall, glycerol is widely used and generally considered low hazard due to its ready biodegradability and low human health risk. While some data gaps remain, it is not classified as carcinogenic or reproductively toxicWhen produced using responsibly-sourced renewable feedstocks and controlled processing methods, the PHA–glycerol strategy reduces dependence on petrochemical plastics and aligns with ECOS requirements for environmental sustainability.

4. Recommendations and Conclusions

HDPE and PETE are made from hazardous chemicals and persist in the environment as microplastics. A safer alternative would match the mechanical and barrier properties, lower hazards, and improve end-of-life outcomes compared to these two incumbents.

Both HDPE and PETE exceed detergent bottle requirements for mechanical strength and barrier performance, providing high durability and strong protection against moisture and oxygen. Despite these favorable properties, our hazard assessment indicates relatively high risks across multiple endpoints, driven largely by additives commonly used in virgin plastic packaging that exhibit high carcinogenicity and systemic toxicity (e.g., benzophenone, PTFE powder). In addition, the monomers of HDPE and PETE themselves present moderate hazard profiles. At end of life, HDPE and PETE are technically recyclable; however, they are often disposed of in landfills, where they fragment into microplastics and release toxic additives.

The first two strategies—paper with PLA-MMT and zein with cutin— match HDPE's mechanical and barrier properties for some key metrics but fall short in others. Both have sufficient tensile strength but will require intentional design and fillers to improve ductility and impact strength. Our third strategy, PHA, matches the HDPE incumbent across all relevant metrics.

In terms of hazards, our first strategy, PLA-MMT paper, presents lower overall hazards than incumbent plastics but may still produce microplastics. Our second strategy, zein with cutin, also has generally lower hazards but does have a few notable high-hazard process chemicals. Finally, our third strategy, PHA, exhibits significantly lower hazards than incumbents. Further research is needed to address hazard data gaps across these novel strategies.

In terms of material fate and sustainability, our first strategy—paper with PLA-MMT—is expected to be industrially compostable, while our second strategy—zein and cutin—is biodegradable and compostable (table XIV). For these strategies, hazards can be further minimized by changing process chemicals and responsibly sourcing the starting materials. Finally, our third strategy, PHA, meets incumbent performance criteria and is biodegradable, compostable, and recyclable.

To more effectively evaluate these solutions, it is necessary to establish the specific technical criteria required for detergent bottles. We used HDPE's properties as a conservative benchmark. However, when comparing the incumbent plastics to each other, HDPE and PETE have very different properties with HDPE outperforming PETE in some criteria and PETE outperforming in others. Because of these large differences, we believe HDPE's properties are not an accurate reflection of the minimum technical criteria needed. We used HDPE as a benchmark for our solutions, but more accurate technical criteria will be able to judge the solutions better and establish what thickness of different layers are required. Additional work is also needed to assess the feasibility of manufacturing these alternatives at scale. Concerns still arise with end-of-life regarding ease of disposal of our strategies. The separate base and coating raise concerns around recyclability and processing. For recycling, each layer will need to be treated differently so they must be separated, which will be difficult and may require special machinery. Other disposal strategies like industrial composting are a better strategy because the separate components will likely be compostable under the same conditions. Furthermore, since ECOS's closures are made of incumbent plastics, consumers would have to cut out the closure and dispose of that separately. In the future, we recommend switching to closures made of greener plastics that are biodegradable or compostable like PLA and PHA, or detergent bottles could be completely redesigned to eliminate the need for a separate closure.

In summary, while each of our alternative strategies presents trade-offs, they all demonstrate the potential to reduce hazards and improve end-of-life outcomes compared with HDPE and PETE. PHA shows the greatest promise in matching incumbent performance while minimizing risks, whereas paper+PLA-MMT and zein+cutin are safer with some mechanical or processing limitations. Continued work to refine technical criteria, optimize manufacturing, and integrate greener closures will be essential for fully realizing safer, sustainable detergent packaging.

Table XVI. Comparison of all strategies, with colors showing the quality benchmarking compared to the incumbent and interpretations on those measurements.

Strategy	Mechanical Performance	Barrier Performance	Hazard Assessment	End of Life
HDPE & PETE	Incumbent	Incumbent	High for many endpoints	Landfill & Recyclable
Paper+PLA+MMT	Good Tensile Strength	Depends on thickness	Potential microplastics	Industrially Compostable
Zein+ Cutin	Good Tensile Strength	Good Oxygen Barrier	From Process Chemicals	Biodegradable/ Compostable
PHA	Meets Incumbent	Meets Incumbent	Most Hazards Reduced	Biodegradable & Recyclable

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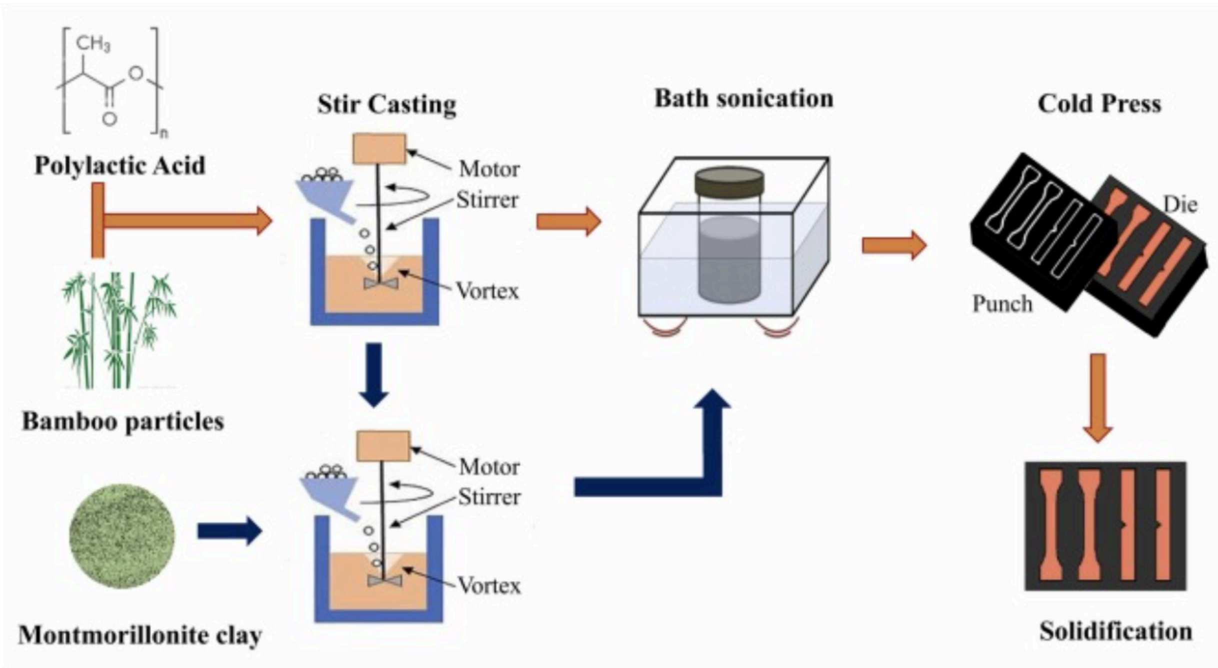
6. Appendices

Appendix I. Process diagram for making the BP + PLA + MMT composite



(Kumar and Babu, 2023)

Appendix II. Complete technical properties table of incumbents and alternatives

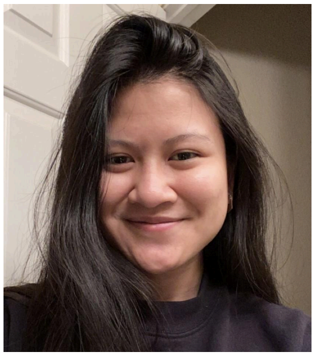
	Mechanical Properties				**Barrier Properties**		**Heat Properties**
	Tensile Strength	Elongation at Break	Impact strength	Elastic Modulus	Water Vapor Transmission Rate	Oxygen Permeability	Melting Temperature
Units	MPa	%	kJ/m2	MPa	g / m2 day (85% RH)	ml/ m2 bar day (85% RH)	°C
HDPE	18 - 20	≥ 380	31	800 - 1000	7.75	703	120 - 140
PETE	55 - 75	≥ 30	4.6	1700	6.9	31	240 - 270
PHB + glycerol	20 - 40	230	20	800 - 3500	5.5	23 - 120*	130 - 170
BP + PLA + MMT	25.85	1.8	7.9	N/A			160
PLA-MMT					11	1012	150 - 180
Zein mixture	22	6.8	2.4	479			N/A ***
Cutin mixture 2					8.8	165 - 736**	76.5

Appendix III. Complete alternatives hazards table

	Group 1 Human Endpoints			Group II and II* Human Endpoints			Ecotoxicity	Fate		Physical Hazards
Chemical	Carcinogenicity & Mutagenicity	Developmental and Reproductive Toxicity	Endocrine Activity	System Toxicity	Neurotoxicity	Skin, Eye and Respiratory Irritation and Sensitization	Aquatic Toxicity Acute & Chronic	Persistence and Bioaccumulation		Reactivity, flammability, PChem traits
Hemicellulose	L	DG	DG	DG	DG	L-M (resp)	DG	DG	VL	M (flammability)
Lignin (polymer)	DG	DG	DG	DG	DG	L-M (resp)	DG	L-M (takes months)	L	M (flammability)
Coniferyl alcohol	DG	M*	DG	DG	DG	DG	DG	DG, likely biodegradable	L	L
Sinapyl alcohol	L*	M*	DG	DG	DG	H (skin, eyes)	DG	DG, likely biodegradable	L	L
p-coumaryl alcohol	DG	DG	DG	DG	DG	L (skin, eyes)	DG	DG, likely biodegradable	L	L
Bentonite / Montmorillonite	DG	DG	DG	L	DG	DG, H (resp)	DG	H	DG	DG
PLA polymer	DG	M	M	M	H	M	H	L	H	Biodegradable, hydrolizable
Lactic acid	L	L	L	L	M	H (skin, eye), M (resp)	L	L	L	Weak acid, metal corrosive
Polybutylene adipate-co-butylene terephthalate (PBAT)	L	M	M	H	H	M	H	L	L	Slowly hydrolyzes
Corn prolamine protein (zein)	VL	L	L	L	DG	L-M	VL	VL	L	Hydrophobic, biodegradable
Cutin *main monomer	DG	L	L	L	L	L	L	L	L	L (flammability)
Chloroform	H	H	H-M	H	H-M	H (skin, eye), M (resp)	M	L	L	L
Hexadecanedioic acid (HDDA)	L	L	DG	DG	L	M	DG	L	L	L
Hydroxyhexadecanoic acid (HHA)	DG	DG	DG	L-M	DG	L-M	L-M	L	M	L (flammability, combustibility)
Dibutyltin oxide	L-M	H	M	H	L	VH(eye)-H(skin, resp)	H	H	H	H
Methanol	L	H-M	H	L	VH	L-M (eye)	L	L	VL	L (reactivity), H (flammability)
Chitosan	L	DG	DG	L	DG	L (resp)	VH	VL	VL	L (reactivity, flammability)
Citric Acid	L	L	DG	M	L	H (eye), L (skin, resp)	L	VL	VL	L (reactivity, flammability)
Glycerol	DG	DG	DG	DG	L	DG	DG	L	L	DG
Sodium Hydroxide	DG	DG	DG	M	DG	VH (skin, eye)	M	VH	DG	M (reactivity)
Hydrochloric Acid	L	M	DG	M	M	VH (eye), M (resp), L (skin)	L	L	L	M (reactivity)
PHA	L	DG	M	L	L	DG	L	L	M	L
Acetone	DG	M	L	M	L	H (eye)	DG	H	DG	H (flammability)
Acetic acid	DG	M	DG	L	L	VH (skin, eye), M (resp)	M	DG	DG	M (flammability), corrosive
Urea-formaldehyde (UF) resin	DG	DG	DG	DG	DG	H (Skin, Resp)	DG	VH-H	DG	Petrochemical

7. Meet the D.R.E.A.M Team

The D.R.E.A.M. team is composed of 5 members, all bringing expertise from different disciplines to solve the challenge.



Deborah Chhun (LinkedIn) is a second-year MPH student in Environmental Health Science with an interest in microplastics, sustainability, and health policy. Her previous work experiences involve research on environmental contaminants and plasticizers (BPA, BPA analogues, acrylamides) impact on maternal and child health, and she currently works at Alameda County, conducting research on flavored vape products and implementing tobacco control policies. Recent in-class projects include assessing microplastic exposure through consumption and research on polyethylene in cosmetics. Deborah completed her B.S. degree in Public Health at CSU, East Bay.

Riya Dutta (LinkedIn) is a third-year chemistry undergraduate student at Berkeley's College of Chemistry, concentrating in materials science. She participated in the undergraduate equivalent course in spring 2024. The partner for that challenge was Habitable and focused on the built environment, specifically creating greener insulation. Through this challenge, Riya learned how to assess health and environmental hazards. In addition, she has some background in polymer chemistry, having taken two classes on polymers and organic chemistry.

Erin Kim (LinkedIn) is a fourth-year chemistry undergraduate at UC Berkeley's College of Chemistry, with a minor in Materials Science Engineering. She has several years of experience in Materials Science Engineering research, where she worked with thin film fabrication, piezoelectric materials, and sensor building in UC Berkeley's College of Engineering. Furthermore, she applied her knowledge of chemistry and materials at Procter & Gamble, where she gained experience in finding biodegradable polymer replacements for current product formulations and innovating smarter, eco-friendly solutions for consumer problems.

Alex Shing (LinkedIn**)** is a second-year MPH student at UC Berkeley's School of Public Health, specializing in environmental health sciences and policy interventions. He has experience in exposure assessment and environmental justice through roles with the U.S. Environmental Protection Agency, academic research, and nonprofit organizations. His recent work has focused on PFAS contamination, mitigation strategies, and translating science into policy recommendations. Alex holds a B.A. in Environmental Biology with a minor in Global Health and the Environment from Washington University in St. Louis.

Mariana Mtanous (LinkedIn) is a Master's student in Bioprocess Engineering at UC Berkeley, focused on leveraging biotechnology and bioprocessing to develop solutions for the biotech and food tech industries. She has several years of experience in food safety regulations, including HACCP, as well as in the research, development, and production of an organic biopesticide for agriculture. Mariana holds a Bachelor's degree in Food Industry Engineering from Tecnológico de Monterrey in Mexico. During her undergraduate studies, she completed coursework in packaging and gained hands-on experience using HDPE for agrochemical packaging.