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Bren School of Environmental Science & Management

Seaweed: The Solution to Pollution?

A Comparative Life Cycle Assessment of LDPE and Algal Flexible Film Packaging

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SIGNATURE PAGE

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The Group Project is required of all students in the Master of Environmental Science and Management (MESM) Program. The project is a year-long activity in which small groups of students conduct focused, interdisciplinary research on the scientific, management, and policy dimensions of a specific environmental issue. This Group Project Final Report is authored by MESM students and has been reviewed and approved by:

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1. Introduction

Forbes called 2021 the Year of the Package (Light 2021). COVID-19 shut down in-person experiences, leading to increased demand for online shopping and accelerated application of single-use plastics as protection from illness. The pandemic contributed an estimated eight million tons of plastic waste to our existing plastic pollution problem (Peng et al., 2021). The COVID-19 pandemic only exacerbated the ongoing plastics problem. Between 1950 and 2015, an estimated 8,300 million metric tons (Mt) of virgin plastic have been produced (Geyer et al., 2017). Common fossil fuel-based plastics do not biodegrade, instead breaking down into microplastics that are increasingly being recognized as a threat to human and environmental health (di Bartolo et al., 2021; Shahul Hamid et al., 2018). If current trends continue, about 12,000 Mt of plastic waste will accumulate in our natural environment by 2050 (Geyer et al., 2017).

The Center for International Environmental Law indicates that packaging accounts for 40% of the global demand for plastics (Light, 2021). The most common packaging material in the fashion industry is low-density polyethylene (LDPE), which is a petroleum-based, nonbiodegradable polymer that has a low production cost and offers flexibility, durability, and impermeability (Jestratijevic and Vrabiˇc-Brodnjak, 2022). However, since the pandemic, a significant portion of fashion brands have committed to plastic-free policies or to transforming all plastic packaging waste into reusable, recyclable, or compostable options (Jestratijevic and Vrabiˇc-Brodnjak, 2022). Surveys conducted by McKinsey found that consumer preferences are shifting to favor products in packaging that they view as environmentally friendly (Feber et al., 2020). An increased awareness of packaging's environmental footprint is driving the development of alternatives that may be more sustainable.

The client, PANGAIA, a materials innovation clothing brand that creates products with an Earth-positive impact, has taken steps to reduce its environmental impact from packaging. Typically, clothing brands do not own their manufacturing processes, so they are often limited by what textile manufacturers develop (Roberts-Islam, 2019). PANGAIA addresses this problem by combining its research and development lab's material innovations with its brand collections (Roberts-Islam, 2019). PANGAIA focuses on improving product performance while lowering environmental impacts through innovation. The company expands access to new fashion technologies across the fashion industry through its open-source platform (About PANGAIA, n.d.). PANGAIA has explored the use of seaweed in its collection, specifically in its trademark water-saving and bio-based fabric called C-Fiber™, which combines wood pulp and seaweed powder (About PANGAIA, n.d.). They pursued this technology because these materials are naturally regenerative, and seaweed does not require fresh water in the growth stage. Currently, PANGAIA uses fully compostable plastic packaging, which is partially sourced from non-GMO corn and sugarcane. PANGAIA believes this is the best sustainable option for shipping, but the company wants to be more confident in ensuring its selected packaging solution aligns with its brand and mission. Therefore, PANGAIA is interested in examining the environmental benefits and tradeoffs of algae-based flexible film through Life Cycle Assessments (LCAs) as a possible alternative packaging material solution.

2. Objectives

This project aims to understand the environmental impacts of algae- and LDPE-based packaging materials to evaluate whether plastic alternatives are more sustainable across several impact categories. We have conducted LCAs to compare different flexible film packaging solutions that are made from LDPE or seaweed. LDPE was selected because it is the industry standard. Seaweed – a term used interchangeably with 'macroalgae' and 'algae' in the report – was selected because it is a next-generation material that aligns with PANGAIA's brand and is not yet thoroughly investigated in existing literature. We analyzed the results of the LCAs using PANGAIA's climate goals and the United States Environmental Protection Agency's (U.S. EPA) Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) impact indicators.

PANGAIA assesses materials using LCAs to provide insight into the environmental impact of their products' lifecycles, from raw materials to manufacturing and distribution (PANGAIA, 2023). PANGAIA measures cradle-to-gate impacts across 13 categories but has chosen to prioritize Blue Water Consumption, Global Warming Potential, and Primary Energy Demand as their impact priorities (PANGAIA, 2023). Overall, PANGAIA intends to minimize its environmental impact. However, the categories assessed in LCA are not fully representative of packaging's impacts, such as the absence of potential microplastic pollution. To address this, the UCSB team compared the tradeoffs between LCA-measured and unmeasured impacts, such as the material's waste footprint, to more holistically compare packaging materials' life cycle impacts.

The UCSB team also deployed a packaging survey to evaluate individuals' access to different waste disposal services and the likelihood of engaging with different disposal methods. The survey findings provide insight into the current status of municipal solid waste disposal and shine some light into what consumers actually have access to and use (e.g. industrial composting, curbside recycling, etc.).

Table 1. *LCA impact categories under examination compared to PANGAIA's material selection priorities.*

TRACI 2.1	PANGAIA
● Global warming potential (GWP) ● Acidification potential (AP) ● Eutrophication potential (EP) ● Smog formation potential (smog) ● Human toxicity (cancer and non-cancer) ● Ecotoxicity	● Minimize environmental impacts of products through comparing TRACI indicators ● Waste reduction ● Decreased fossil fuel dependency ● Alignment with company values

Our project objectives are as follows:

I. Complete an LCA of LDPE plastic film packaging
II. Complete an LCA of algal flexible film packaging
III. Compare LCAs and other environmental factors to holistically evaluate each packaging material's environmental benefits and tradeoffs
IV. Design and analyze a survey focused on PANGAIA consumers' access to waste hauling services and their current waste sorting habits

3. Background and Literature Review

3.1 Low-density Polyethylene (LDPE)

LDPE is a strong, flexible film, and it is a common packaging solution for bags (such as grocery, dry cleaning, and garbage) and plastic wraps. Although technically recyclable, LDPE films are rarely recycled through curbside pickup programs. To be recycled, LDPE needs to be brought to designated plastic film collection facilities because material recovery facilities will landfill LDPE (Plasticfilmrecycling.org). Additionally, consumers are often unaware that LDPE films cannot be processed through curbside recycling or are unable/unwilling to take LDPE to a designated facility. If the material does make it to a designated recycling facility, mechanical recycling processes are often inefficient, resulting in a plastic quality decline with each round of recycling. Ultimately, recycled material is less useful than its virgin counterpart (Chia et al., 2020).

LDPE that is not recycled or landfilled often ends up in the environment. Some LDPE plastics can biodegrade under specific lab conditions but are unlikely to degrade fully in the environment

(Kyaw et al., 2012). When LDPE degrades in the environment, it breaks up into harmful microplastics (Devadas et al., 2021). Microplastics are plastics that measure between five millimeters and two nanometers in diameter (Rodrigues et al., 2019). So much microplastic pollution is in our environment that it is accumulating in our oceans, soils, and even our food.

3.1.1 Manufacturing and Process Diagram

Polyethylene is the most manufactured plastic by weight, with a simple polymeric structure of repeating CH_2 units (Ronca, 2017). Polyethylene has ideal mechanical properties, processing properties, and chemical stability; it is temperature, chemical, pressure, and radiation-resistant (Zhong et al., 2018).

The first stage of polyethylene production begins with the extraction and refinement of fossil fuels. Next, steam cracking is used to break down saturated hydrocarbons into smaller, unsaturated hydrocarbons (Ronca, 2017). During this process, a large amount of ethylene is produced from petroleum sources such as naphtha, ethane, and sometimes propane or butane (Ronca, 2017). Although crude oil is a large source for producing polyethylene, natural gas is also used as a feedstock (U.S. EIA, 2021).

Next, polymerization occurs, which includes opening a monomer’s double bond to link additional monomeric molecules and form a saturated long-chain macromolecule (European Commission, 2007). Polyethylene can be considered low-density or high-density based on its molecular structure (Zhong et al., 2018). The polyethylene produced using high pressure is called low-density polyethylene.

There is limited, publicly available information about high-pressure commercial polymerization processes, but most are produced using 100-300 MPa and 80-300 degrees Celsius temperatures (Ronca, 2017). The general process varies based on the reactor type, which is either a stirred vessel or a tubular reactor (European Commission, 2007). The tubular process generally makes resins with optimal optical properties whereas stirred processes make more homogeneous copolymer products and ideal extrusion coating resins (European Commission, 2007). Any untreated ethylene is recovered and recycled, and treated/untreated ethylene is separated by pressure (Zhong et al., 2018). After polymerization, the mixture of unreacted ethylene gas and polyethylene is fed to a separator where it is depressurized and then recycled to the compressor through a filter (Japan International Cooperation Agency). Lastly, the leftover polyethylene is extruded to be pelletized (Japan International Cooperation Agency).

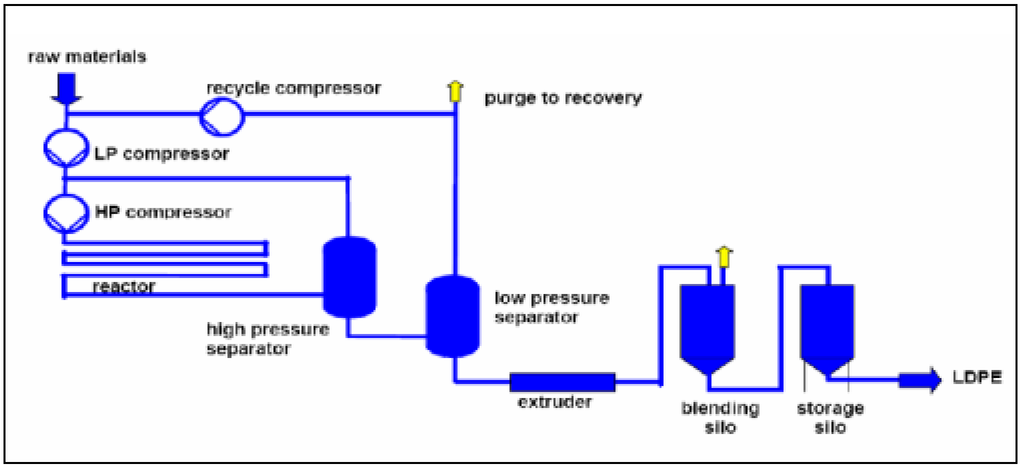

Figure 1. *Flow diagram showing LDPE production (European Commission, 2007).*

3.1.2 LDPE Benefits

LDPE is a highly flexible material that has low-temperature impact toughness, low-temperature impact resistance, and chemical degradation resistance (Pham, 2021). LDPE is vapor-proof, making it an effective protective and insulating material in construction and agricultural applications (Szlachetka et al., 2021). LDPE is technically recyclable, but the recycled polymer does not exhibit properties feasible for reuse in many applications (Pham, 2021). New outlets for recycled LDPE combined with virgin polymers are being investigated to produce improved mechanical properties, such as adding ethylene-vinyl acetate (EVA) to increase resistance to environmental stress cracking and tearing (Pham, 2021).

The chemical industry consumes about 28% of industrial and 10% of global energy (Birol, 2017). Most of this energy is obtained from oil or other fossil resources used as carbon feedstock or to generate process energy (Birol, 2017). Overall, the chemical industry emits over 3.3 billion metric tons (Mt) of CO_2 per year (Kätelhön et al., 2019). Within the industry, plastics account for 1.8 billion Mt of CO_2 per year (Zheng and Suh, 2019). Although these greenhouse gasses and plastic waste contribute to environmental degradation, there is potential to use CO_2 as a carbon source for plastic production, which would both reduce emissions and provide a service (Zheng and Suh, 2019). Carbon capture and utilization (CCU) in the chemical industry could provide a renewable source of carbon compounds and address carbon sequestration economic challenges (Kätelhön et al., 2019). Nonetheless, one tradeoff is if CCU was scaled to the entire industry, the industry's total energy demand would increase from hydrogen use, necessitating a significant increase in low-carbon electricity (Kätelhön et al., 2019). More research is needed on the benefits of storing CO_2 in plastics.

3.2 Algal Flexible Film

In the 20th century, intentional seaweed cultivation began and has since expanded across Asia (Radulovich et al., 2015). More recently, seaweed cultivation has become common within Europe (van Oirschot et al., 2017). Researchers have become increasingly interested in seaweed's potential as a material input for various household goods such as toothpaste, cosmetic cream, food supply, and biofuel production. This is because seaweed contains useful proteins, lipids, and carbohydrates (Thomas et al., 2021). Polysaccharides are a useful carbohydrate group that can be derived from seaweeds. These polysaccharides are known as phycocolloids, and they can be combined with other substances to create flexible films (Lomartire et al., 2022). With careful design, these films can provide the strength necessary to act as a flexible film packaging solution, but their use as plastic alternatives is still in its infancy.

Seaweeds require minimal inputs, such as fertilizers and pesticides, while also performing ecosystem services, such as providing habitat for hundreds of marine species across the world (Thomas et al., 2022). Although there are several ecological benefits from seaweed production, there are also negative environmental consequences that may amplify as seaweed production scales. Research has shown that a potential tradeoff associated with utilizing seaweed is that extracting and processing the plant's useful materials may be energy- and resource-intensive (Dang et al., 2022). Other potential negative consequences include biodiversity loss, shading, and the introduction of invasive species (van Orishot et al., 2017; Eggersten and Halling, 2020). Concerns about the environmental impacts associated with over-harvesting unmanaged seaweed stocks are growing, resulting in seaweed cultivation becoming more common (van Oirschot et al., 2017; Mac Monagail et al., 2017). Seaweed production must be carefully evaluated to ensure that its transition to large-scale use does not have an overall negative environmental impact.

3.2.1 Seaweed Production and Harvest

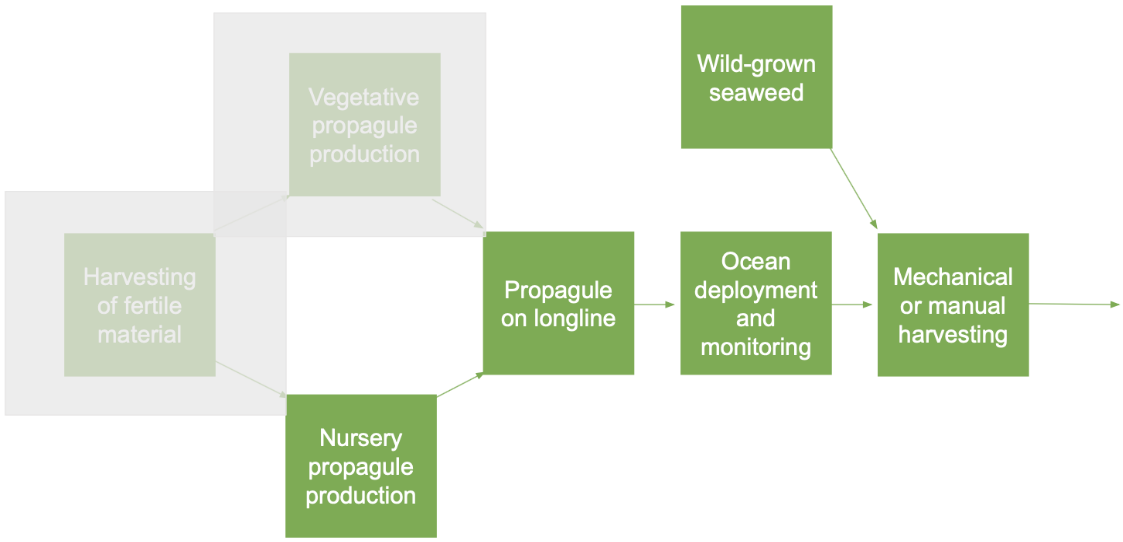

Figure 2. *System boundary for seaweed cultivation and harvest, with steps excluded from analysis, indicated with grayed-out boxes.*

The system boundary for our analysis is shown in Figure 2 above. We identified two seaweed spore propagation pathways: nursery propagule production and vegetative propagule production. The former involves growing spores in a lab setting under controlled conditions, and the latter uses cuttings from prior years' harvests to propagate new plants. Nursery propagation allows for more control over the quality of spores, but vegetative propagation is easier and requires fewer material inputs (Radulovich et al., 2015). Due to a lack of life cycle inventory data for vegetative propagation, our assessment only includes the nursery pathway based on research performed by *Thomas et al.* in 2021. This pathway involves propagules being added to a nutrient mix solution and then attached to a polypropylene seeding line by spraying it onto the line. Once the spores have grown into gametophytes of sufficient size to survive at sea, they are deployed (van Oirschot et al., 2017; Thomas et al., 2021).

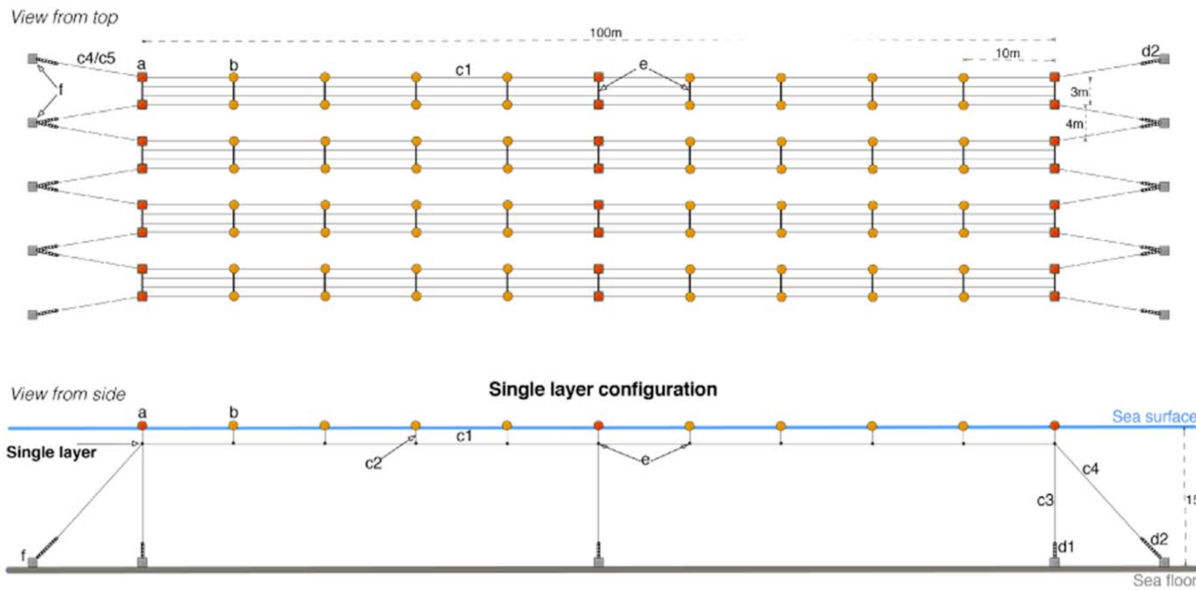

Figure 3. *This figure was produced and published by van Oirschot et al. (2017). It shows a representation of longline cultivation infrastructure viewed from above and from the side, with components indicated according to the following: (a) marker buoys, (b) small buoys, (c) polypropylene rope (longline), (d) steel chain, (e) strip strengtheners, and (f) concrete anchors.*

The seeded lines are attached to a longline structure for ocean growth. The at-sea cultivation structure as shown in Figure 3 involves longlines (polyester, polypropylene, or polyamide), anchors (concrete), chains and shackles (stainless steel), buoys (PVC or polyethylene), and ropes (polypropylene) (van Oirschot et al., 2017; Thomas et al., 2021). Though longlines can be arranged in two layers, one at the surface and one below the surface (van Oirschot et al., 2017), we assumed a single layer for our analysis. Cultivating seaweed requires occasional visits via boat for maintenance, monitoring, and harvest. As with wild harvest seaweed, cultivated seaweed is harvested mechanically and manually (Thomas et al., 2021).

3.2.2 Seaweed Processing

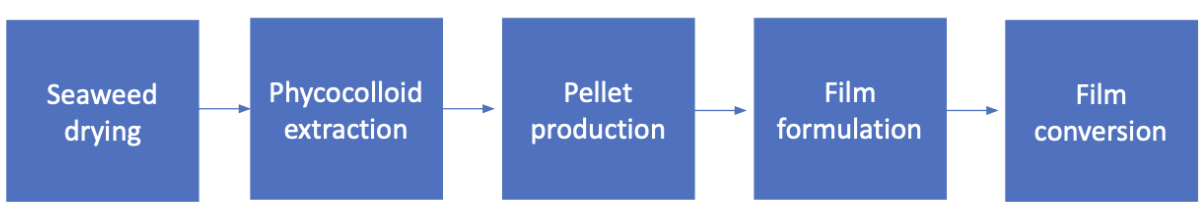

Figure 4. *System diagram for seaweed processing from seaweed drying to film conversion.*

Prior to algae processing, the seaweed must be dried. It carries significant water weight that is inefficient to transport and must be removed to derive the valuable seaweed components. We modeled two drying options: hang drying and air cabinet drying based on life cycle inventory data from *Nilsson et al.* (2022).

Seaweed-derived biological compounds have unique physical, mechanical, and thermal properties that make them ideal for flexible film production (Lomartire et al., 2022). Phycocolloids are high molecular weight polysaccharides composed of sugar polymers (Pangestuti and Kim, 2015). They are the main structural components of seaweed cell walls (Pangestuti and Kim, 2015). Phycocolloids play different functional roles, like forming a gel at room temperature, because of their ability to hold significant amounts of water (Pangestuti and Kim, 2015). Phycocolloid can refer to three main components that are extracted from red and brown seaweeds: agar, carrageenan, and alginates (Pangestuti and Kim, 2015). Phycocolloid will be used as the general term for those three main components in this project.

Due to literature data availability, our modeled life cycle inventory data for seaweed nursery, cultivation, and harvest is for the species *Saccharina latissima* and the phycocolloid used in our seaweed processing modeling is alginate. Alginate is the compound most frequently used for flexible film production. It is extracted from brown seaweeds, usually from the genera *Laminaria* and the species *Ascophyllum nodosum*, and derived from alginic acid (Lomartire et al., 2022). When calcium is added to the alginate matrix, there is more stability and resistance provided to the membrane (Lomartire et al., 2022). Additionally, films made from sodium alginate with a calcium chloride solution have increased tensile strength and elongation properties, as well as reduced opacity (Lomartire et al., 2022).

To obtain sodium alginate, algae are chopped and then chemically treated (Piccinno et al., 2015). Then, an ionic exchange in a hot solution of Na_2CO_3, or another alkali agent, extracts the sodium alginate from calcium alginate (Piccinno et al., 2015). When water is added, the insoluble parts are separated by filtration (Piccinno et al., 2015). Alginic acid is formed when an acid is added to the solution (Piccinno et al., 2015). The solution is dewatered before mixing with ethanol or another alcohol agent (Piccinno et al., 2015). Lastly, gradually adding solid sodium carbonate or another alkali agent yields sodium alginate (Piccinno et al., 2015). Most sodium alginate extraction processes follow these general steps, but there may be variations in the agents and quantities used.

An initial cradle-to-gate LCA of alginate extraction found that the process had a better environmental performance when there was a higher alginate yield (Nilsson et al., 2022). Despite higher energy consumption in some steps, a higher alginate yield meant fewer inputs were necessary to produce the same amount of product (Nilsson et al., 2022). It may be possible to generate co-products during the extraction of sodium alginate, allowing the environmental impacts of the process to be divided among multiple useful co-products (Nilsson et al., 2022). See the data and methods section for a discussion of how co-products were modeled for this study.

3.2.3 Film Production

Due to the relatively new technologies used to create algal flexible films, there is minimal literature on the film production life cycle stage and inventory data. Due to this gap in available science, primary data was acquired from three seaweed flexible film producers, who we will refer to as our data partners. Generally, this process consists of converting our processed phycocolloid into plastic film, using energy and, in some cases, a co-substrate.

3.2.4 Seaweed Benefits

Seaweed aquaculture provides ecosystem services that should be considered for seaweed-based plastics. The following ecosystem services have been identified in our literature review: nutrient uptake, maintenance of human livelihoods, habitat provision, CO_2 sequestration, augmentation of wild fisheries, tourism, increasing water clarity, acidification regulation, and coastal protection (Gentry et al., 2019; Umanzor and Stephens, 2023). Our team focused on ecosystem services that pertain to our client's priorities and TRACI 2.1 impact categories.

Ocean Acidification Buffering

Since the Industrial Revolution (1760-1840), near-surface ocean waters have acidified around 0.1 pH units (Romera-Castillo et al., 2023). In 2018, ocean plastic pollution was estimated to be 13 million metric tonnes (Romera-Castillo et al., 2023). These two environmental threats have continued to worsen with time (Romera-Castillo et al., 2023). Plastic leaching alters the biogeochemistry of the ocean through released dissolved organic matter. Additionally, abiotic plastic degradation induces a decrease in seawater pH, especially as plastic ages (Romera-Castillo et al., 2023). For the latter, acidification is enhanced by solar radiation and can lead to a seawater pH decrease of up to 0.5 units in coastal areas with large amounts of plastic pollution (Romera-Castillo et al., 2023).

Although the global solution to ocean acidification is greenhouse gas emissions reduction, seaweed aquaculture has been proposed as an adaptation strategy to address localized ocean acidification (Xiao et al., 2021). Kelp forests' ability to uptake dissolved inorganic carbon (DIC) allows them to modify local seawater chemistry. By taking up bicarbonate and CO_2 as a carbon source for photosynthesis, kelp forests reduce nearby acidity and increase dissolved oxygen. This creates conditions conducive to calcification (Murie and Bourdeau, 2020). Natural kelp forests have been decreasing in canopy cover from recent environmental stressors, but studies found that fragmented kelp still can increase pH during the growing season's daylight hours (Murie and

Bourdeau, 2020). Studies support seaweed farming's ability to provide local adaptation to ocean acidification and deoxygenation, with the most efficient species being *S. japonica* due to its high photosynthetic rate and high biomass density (Xiao et al., 2021).

Carbon Sequestration

Blue Carbon (BC) strategies were developed to mitigate and adapt to climate change through conserving and restoring vegetated coastal ecosystems, which show the potential to sequester and store carbon (Krause-Jensen et al., 2018). Specifically, scientists have speculated that green and brown seaweed can utilize CO_2 in photosynthetic processes to sequester carbon (Mashoreng et al., 2019). Macroalgae, the most productive vegetated coastal habitat in the global coastal ocean, is estimated to cover 3.4 million km^2 and support a global net primary production of about 1.5 PgC yr^{-1} (Krause-Jensen et al., 2018). There is also potential for high ecological risks that have not yet been quantified, adding some skepticism to the viability of seaweed as a mechanism for BC storage (Ross et al., 2022).

Concerns surrounding temporal measures and other complexities result in uncertainty about the impact and amount of carbon sequestered from seaweed aquaculture (Troell et al., 2022). The estimates of scale are up for debate as well; some calculate that seaweed aquaculture has a theoretical maximum annual sequestration of 72 billion tonnes, which is larger than global annual emissions (Duarte et al., 2017). Most carbon fixed by seaweed is only briefly stored as biomass before it is rereleased when the plant decomposes, meaning that carbon in seaweed predominantly enters the fast carbon cycle and is not sequestered for a long period of time (Troell et al., 2022). However, emerging research demonstrates that seaweed may sequester carbon in soils over a longer time period than it sequesters carbon in its biomass. Researchers found carbon sequestered in the underlying sediments at varying rates below seaweed farms (Duarte et al., 2023). This may dispel concerns that seaweed's carbon sequestration will only occur in the short term (Duarte et al., 2023). Whether it is economically feasible to achieve long-term sequestration at scale is unclear, but research is still being conducted on ecological, technical, and economic feasibility (Ross et al., 2022).

Nutrient Uptake

Coastal eutrophication, which is often caused by excess nitrogen and phosphorus, negatively impacts ecosystem health, food security, and the economy (Malone and Newton, 2020). Macroalgae require multiple nutrients for growth, mainly nitrogen and phosphorus, so their growth uptakes these eutrophication-causing nutrients (Fei, 2004). Between 2017 and 2019, *Xu et al.* (2023) monitored six kelp (*Saccharina japonica*) farm sites in northern China to assess nutrient uptake. In the study, the annual nitrogen and phosphorus removal through kelp aquaculture was approximately 104 tons and 12 tons, respectively (Xu et al., 2023). In *Marinho et al.* (2015), two commercial cultivation areas in Denmark of *Saccharina latissima* were assessed for bioremediation potential over 12 months; *S. latissima* showed potential for assimilation and removal of nutrients, particularly nitrogen (Marinho et al., 2015).

3.3 Survey

The fashion industry's standard packaging is LDPE flexible film (Holding et al., 2019). The pressure on fashion companies to move away from fossil-based plastic packaging is increasing (Feber et al., 2020). The end-of-life treatment of a material, based on individuals' waste-sorting behaviors, has a significant influence on its environmental profile. For example, when compostable materials are incorrectly sorted into airtight landfills, they do not receive the required oxygen that is necessary for their breakdown. As a result, these materials may break down anaerobically (U.S. EPA, 2019). This anaerobic decomposition leads to greenhouse gas emissions, primarily methane, which may greatly influence a material's associated environmental impacts (U.S. EPA, 2019). Methane emission is a concern because it has roughly 30 times the warming potential of CO_2 over 100 years, meaning that, although methane is around for a shorter time, it contributes significantly to global warming (U.S. EPA, 2022).

When examining US and UK households' access to waste services and their waste sorting practices, it is apparent that compostable materials are frequently not composted. In the US, access to composting services is extremely limited. Oregon Student Public Interest Research Group found that in the US, 326 towns and cities have access to food waste curbside collection, which accounts for less than 2% of Americans (Michal, 2022). In the UK, households that do have access to composting services demonstrate limited participation in composting. BusinessWaste.co.uk found that the majority of people do not compost food waste even when compost hauling is provided by their municipality. Of the households that did have access to compost hauling, only 10% indicated that they take part in curbside composting (Hall, 2014).

With this understanding, we created our survey to better understand how access to waste services and waste sorting practices will affect the environmental impact of PANGAIA's potential packaging solutions. We designed this survey to improve our understanding of another environmental benefit from compostable packaging materials – waste reduction – that is not represented in the LCA impact categories.

4. Data & Methods

4.1 Life Cycle Assessments

The purpose of LCA is to quantify and assess the cradle-to-grave or cradle-to-gate life cycle impacts for a product or service. By analyzing impacts at the scale of individual unit processes, decision-makers can assess which processes are environmentally intensive and target actions to reduce impacts. Our team quantified the impacts of LDPE film and algal flexible film using the LCA framework as defined by ISO 14044.

TRACI 2.1 is an environmental impact assessment tool developed by the U.S. Environmental Protection Agency that characterizes and quantifies environmental stressors across impact categories including global warming potential (including and excluding biogenic carbon), acidification potential, eutrophication potential, smog formation potential, human toxicity potential (cancer and non-cancer), and ecotoxicity potential. Characterization factors quantify potential inputs and releases across impact categories in common equivalence units to facilitate easy comparison and interpretation across each life cycle inventory (LCI) process (Bare, 2012).

The four stages of a life cycle assessment are:

1. Goal and Scope Definition
2. Inventory Analysis
3. Impact Assessment
4. Interpretation

4.1.1 Goal Definition

Our goal is to assess and compare the environmental impact of algae-based flexible films and LDPE film from raw material extraction to end-of-life (cradle-to-grave). We pair the LCA analysis with additional considerations that are not visible through traditional LCA methodology to inform PANGAIA of the environmental benefits and tradeoffs from LDPE film and algal flexible films. The purpose of this study is to:

1. Understand the environmental impacts of LDPE and seaweed-based flexible film packaging by comparing a Life Cycle Inventory Assessment (LCIA) for each film;
2. Assess other environmental impacts, such as waste footprint, that are not accounted for in LCA;
3. Analyze access to waste services, waste sorting behaviors, and PANGAIA's environmental priorities;
4. Highlight methods that the algal flexible film industry can use to reduce their environmental impact.

The intended audience of the study is PANGAIA, our data partners, and UCSB faculty for a review to fulfill the requirements of the Bren School of Environmental Science & Management Master of Environmental Science and Management curriculum.

4.1.2 Scope Definition

For the LDPE packaging option, the system boundaries include all unit processes in the life cycle system model (Figure 1). The system for our cradle-to-grave analysis includes crude oil extraction, polymer production, packaging manufacturing, cumulative transportation, and end-of-life treatments.

For the algal flexible film, the system boundaries include all unit processes in the material's life cycle system model (Figure 2). The stages within our system boundary are hatchery propagule production, cultivation, harvesting, drying, phycocolloid extraction, pellet production, and film extrusion.

For both materials, we did not include distribution because a company does not determine distances for product delivery. We assumed that because both materials serve the same function, their distribution impacts would be roughly equivalent. Additionally, the use phase is not considered because packaging is typically discarded immediately after opening.

To compare product systems of different materials, we established a functional unit that describes the desired utility of the product. We compare life cycle inventories of different product systems by normalizing all inputs to the reference flow, or the amount of material necessary to achieve the utility of the functional unit.

The functional unit (FU) in this study is a 40 cm x 30 cm flexible film bag of sufficient thickness to safely deliver a product from producer to consumer. These dimensions were selected as an approximation of a "polybag" (or garment primary packaging) mailer bag size used by the garment industry, but sizes do vary across and within companies depending on what is being shipped. We considered density and thickness when selecting the reference flow that represents an equivalent function across material types. The reference flow for the LDPE plastic packaging is 12 grams. The reference flow for the macroalgae flexible film is 18 grams. Data from our partners shows that the seaweed flexible films are more dense than LDPE, so we see that the necessary system output is greater to yield the same function.

4.1.3 Inventory Analysis

Our team conducted LCAs using the GaBi database content version 2022.2 and software version 10.6.2.9 from Sphera, combining primary data, literature data, and built-in GaBi datasets to create our models. GaBi contains background data for production processes that assign environmental impacts to the inventory materials we input and scales them to our reference flow.

For the LDPE model, we used an existing inventory model in GaBi that represents a compilation of industry data. Table 2 describes the full LCI for this process. We selected U.S. processes because the data was from a trusted data source with up-to-date values. Other potential sources were eliminated for having expired data.

Table 2. *LCI for cradle-to-gate LDPE film production sourced from built-in Sphera datasets.*

Inventory item or process	**Selected GaBi process**	**Quantity per 1 kg of LDPE**	**Unit**
Thermal energy	US: Thermal energy from natural gas	0.208	MJ
Electricity	US: Electricity grid mix	1.67	MJ
Lubricants	US: Lubricants at refinery	0.000201	kg
LDPE granulate	US: Polyethylene Low Density Granulate (LDPE/PE-LD)	1.04	kg

We collected primary data from seaweed flexible film producers and used literature sources to build out a full life cycle inventory. These data partners do not oversee seaweed propagation and harvest, so the life cycle inventory data for seaweed hatchery, cultivation, and harvest were taken entirely from literature as seen in Tables 3, 4, and 5, respectively (Thomas et al., 2021). Life cycle inventories for drying and phycocolloid extraction were taken from a seaweed-based biorefinery concept for the production of food, materials, and energy, found in literature as seen in Tables 6 and 7, respectively (Nilsson et al., 2022). The rest of the seaweed processing to final film conversion data is based on primary data collected by three data partners. When building our models in the GaBi software, we selected built-in plans and processes whose supporting data sets provided the greatest geographic and temporal accuracy.

Table 3. *LCI for seaweed hatchery (Thomas et al., 2021), adjusted to 1 kg of wet seaweed output.*

Inventory item or process	**Material**	**Quantity per 1 kg of wet seaweed biomass**	**Unit**
Aeration and stirring system	Energy	4.46E-03	MJ
Aquaria	Acrylic Perspex	2.91E-04	kg
Autoclave	Energy	1.68E-04	MJ
Bucket	Polyethylene	1.13E-05	kg

Collectors	Polyvinyl Chloride	2.75E-04	kg
Lighting System	Electricity	2.08E-02	MJ
Nutrient mix	Proprietary Mix	4.01E-04	L
Seawater filters	Polypropylene (90%), 18/8 steel (10%)	3.36E-05	kg
Seawater source and filter system	Energy	5.45E-05	MJ
Seedling line	Nylon	1.58E-04	kg
Temperature control system	Energy	1.55E-02	MJ
Water heating system	Energy	1.20E-03	MJ

Table 4. *LCI for seaweed cultivation (Thomas et al., 2021), adjusted to 1 kg of wet seaweed output.*

Inventory item or process	**Material**	**Quantity per 1 kg of wet seaweed biomass**	**Unit**
Anchor	Concrete	2.83E-05	kg
Anchoring Buoy	Polyethylene	6.56E-04	kg
Marker Buoys	Polyvinyl Chloride	5.68E-04	kg
Chain	Low-alloy Steel	2.55E-03	kg
Longline	Polyester Silk	3.61E-03	kg
Longline	Polypropylene	8.53E-04	kg
Vessel	Barge	3.92E-03	kgkm
Shackle	Low-alloy Steel	1.47E-04	kg

Table 5. *LCI for seaweed harvest (Thomas et al., 2021), adjusted to 1 kg of wet seaweed output.*

Inventory item or process	**Material**	**Quantity per 1 kg wet seaweed biomass**	**Unit**
Vessel	Motorized barge	21.7	kg/km

Table 6. *LCI for seaweed drying (Nilsson et al., 2022), adjusted to 1 kg of wet seaweed output.*

Inventory item or process	**Input**	**Quantity per 1 kg wet seaweed biomass**	**Unit**
Energy for drying	Electricity	3.17	MJ

Table 7. *LCI for phycocolloid (alginate) extraction (Nilsson et al., 2022), adjusted to 1 kg of alginate output.*

Inventory item or process	**Quantity per 1 kg of alginate**	**Unit**
Calcium chloride (was not available in GaBi so used Sodium Chloride as a proxy)	0.20	kg
Electricity	14.96	MJ
Heat	0.19	MJ
Hydrochloric acid	0.82	kg
Seaweed	2.96	kg
Sodium bicarbonate	0.41	kg
Sodium chloride	0.07	kg

Table 8. *LCI for the creation of co-products from phycocolloid (alginate) extraction (Nilsson et al., 2022), adjusted to 1 kg of alginate output.*

Inventory item or process	**Quantity per 1 kg of alginate**	**Unit**
Inputs for cellulosic film production		
Electricity	0.17	MJ
Heat	1.33	MJ
Potassium Hydroxide (KOH)	0.23	kg
Inputs for anaerobic digestion		
Electricity	1.07	MJ
Heat	1.04	MJ

Co-products		
Cellulosic Film (Substituting with PLA)	0.34	kg
Electricity	2.95	MJ
Fertilizer (NH_3)	0.22	kg

Table 3 outlines the life cycle inventory model for our seaweed hatchery, from *Thomas et al.* (2021). It should be noted that the pre-spore preparation phase includes the selection of a parent specimen and the acquisition of spores from this species. These inputs vary case-by-case and are therefore omitted from this study (Thomas et al., 2021). It is important to understand the characteristics of the parent species since it may alter the intended final product yield (Schiener et al., 2015). The seaweed cultivation LCI includes the materials required for the offshore farm system and the spore propagation longline requirements. Our model follows *Thomas et al.* (2021), and we made no omissions. Values in the table are scaled to 1 kg of wet seaweed biomass. Table 5 shows the energy service needed to harvest one kilogram of wet seaweed. Drying and algae processing LCIs were extracted from Nilsson et al. and were scaled to our functional unit. Electricity inputs for drying were confirmed with water evaporation calculations and water's latent heat of evaporation. As noted in Table 7, NaCl was used as a proxy for $CaCl_2$ in the phycocolloid extraction process. No inputs were excluded in this step; however, further inputs were modeled in our scenarios that include co-products (Table 8) and avoided burden. Because we are under non-disclosure agreements with our data partners, no inventory models for the final phases of the supply chain are available.

As flexible film production from seaweed is an emerging field, several assumptions have been made to account for gaps in the existing literature, as seen in Table 9.

Table 9. *Modeling assumptions and data sources.*

Unit process	Assumption	Source
Nursery, cultivation, and harvest	Seaweed nursery, cultivation, and harvest inventory data	Thomas et al., 2021
	Seaweed species – *Saccharina latissima* (S. latissima)	Thomas et al., 2021
	Seaweed yield from single-level longline system	Thomas et al., 2021
	Seaweed dry mass as a percent of wet mass (10%)	Sondak et al., 2017

	Seaweed carbon content as a percent of dry mass (30%)	Sondak et al., 2017
	Seaweed carbon sequestration potential (110g CO_2/kg wet seaweed)	Our own calculation
	Seaweed nitrogen content as a percent of dry mass (2.28%)	Marinho et al., 2015
	Seaweed nitrogen sequestration potential (10.1g NO_3^-/kg wet seaweed)	Our own calculation
	Seaweed phosphorus content as a percent of dry mass (0.44%)	Marinho et al., 2015
	Seaweed phosphorus sequestration potential (1.34g PO_4^{3-}/kg wet seaweed)	Our own calculation
Phycocolloid extraction	Phycocolloid extraction inventory data	Nilsson et al., 2022 (optimization 5)
	Seaweed species – *S. latissima*	Nilsson et al., 2022
	Seaweed dried after harvesting and before alginate extraction	Nilsson et al., 2022
	Alginate extraction rate (33.8%)	Nilsson et al., 2022
	Avoided burden of extraction from co-products (see further detail below)	Nilsson et al., 2022
	Liquid residue from alginate extraction not further processed – modeled as waste	Nilsson et al., 2022
End-of-life	Percentages of plastic and food waste to waste streams	Milbrandt et al., 2022; U.S. EPA, 2020
	Calorific value and carbon content of seaweed flexible film	Partner data; our own calculation

4.1.4 Modeling Co-products (Avoided Burden Approach)

Additional useful products can be extracted during the biorefinery model that extracts phycocolloid from seaweed. These products include film produced from cellulosic residues, electricity from biogas, and fertilizer (NH_3) from a digestate (Nilsson et al., 2022).

We modeled these co-products using the avoided burden approach. This approach recognizes that without the phycocolloid extraction process creating these co-products, they would have been produced independently through another system. Because these additional co-products were produced during the phycocolloid extraction process, their environmental burden was avoided. We modeled this by first subtracting the burden of creating a co-product as part of another system and then adjusting the impacts for phycocolloid extraction by distributing them amongst the co-products. We modeled the burden of avoiding polylactic acid creation (a proxy for the cellulosic film), electricity generation (from burning biogas produced in an anaerobic digester with film production residue as a digestate), and fertilizer production (from the digestate after treatment in the anaerobic digester) (Nilsson et al., 2022).

The co-products are included in some modeled scenarios, with the avoided burden approach used to distribute the environmental impacts amongst all products. Additional inputs to create electricity and fertilizer co-products include electricity and heat for anaerobic digestion. To produce the cellulosic film co-products, electricity, heat, and potassium hydroxide are added to the system. These inputs were included in our models that account for co-products, as seen in Table 8.

4.1.5 End-of-Life

For LDPE film, the end-of-life pathways were modeled using plastic waste end-of-life data from the U.S. Department of Energy's National Renewable Energy Laboratory, specifically for LDPE resin. The three pathways and corresponding pathway percentages for LDPE resin are as follows and can be found in Table 10: landfill (88%), incineration for energy recovery (10%), and recycling (2%) (Milbrandt et al., 2022). These pathways and percentages were used to model the end-of-life pathways for LDPE in GaBi.

For the algal flexible film, there was no primary data available on its end-of-life treatment due to its novelty. Since the algal flexible film producers stated that this flexible film decomposes without requiring industrial composting, we used data for food waste as a proxy. Available food waste end-of-life data covered only 71.9% of food waste with 28.1% left uncategorized. Accordingly, we scaled the percentage entering each waste stream with 71.9% as the total (U.S. EPA, 2020). The three pathways and corresponding pathway percentages for the seaweed flexible film are as follows and can be found in Table 10: landfill (77.75%), incineration for energy recovery (16.55%), and composting (5.7%). It should be noted that the actual composting rate for seaweed flexible film could be lower if consumers do not recognize it as a compostable material.

We modeled the incineration pathway using a GaBi process for plastic waste incineration since no background data exists for incineration of seaweed flexible film. Because seaweed flexible film has a lower carbon and energy content than petroplastics, we adjusted the amount of energy generated and the amount of CO_2 emitted by this process. Additionally, we modeled the landfill pathway using a plastic waste in landfill process because data is not available on how seaweed flexible film behaves in an anaerobic landfill environment.

For both materials, we modeled the avoided burden of electricity generated from waste incineration. For LDPE recycling, we modeled the avoided burden for LDPE primary production that is mitigated by recycling. We did not model avoided burden for the compostable material resulting from composting the algal flexible film because the production was minimal and the database lacks a compost material process. Although compost can be used as a fertilizer, we chose not to avoid the production of fertilizer because the two materials may not be analogous and compost may not be used in the same way as fertilizer.

Table 10. *U.S. food and LDPE disposal pathways. For food disposal pathways, the data was collected from the EPA, and for LDPE disposal pathways, the data was collected from the Department of Energy's National Renewable Energy Laboratory (Milbrandt et al., 2022; U.S. EPA, 2020).*

Material	**Landfilling as percent of generation**	**Incineration as percent of generation**	**Recycling as percent of generation**	**Composting as percent of generation**
LDPE	88%	10%	2%	N/A
Food waste proxy	77.75%	16.55%	N/A	5.7%

4.2 Survey

We conducted a survey to gain an understanding of access to various waste services and common waste sorting behaviors. We completed a Survey Instrument Matrix to establish key research questions that the survey attempted to answer. The matrix helped identify our hypotheses that access to waste services and waste sorting behaviors has a significant impact on a packaging material's end-of-life environmental impact. These hypotheses were informed by an extended literature review specific to the end-of-life impacts of the two packaging options and consumer waste sorting behavior. The survey was created with Typeform, and PANGAIA recruited survey participants by promoting the survey to the company's LinkedIn page. PANGAIA employees and the UCSB team also shared the post with their LinkedIn networks. The survey's questions and answer choices can be seen in Table 11.

Our research questions were as follows:

1. How do recycling and composting rates compare to each other?
2. How strong is the correlation between access to a waste service and engagement with that waste service?

Table 11. *Survey questions and answer options that were included in the packaging survey. The answer options for questions 2-6 are randomly shuffled for each survey participant to address the Primacy Bias, or the tendency for respondents to pick one of the first options presented to them. If a survey respondent answered that they have not bought a PANGAIA product, questions 2 and 4 were excluded from their survey.*

Number	**Question**	**Answer options**
1.	Have you bought a PANGAIA product before?	A. Yes B. No
2.	After you opened your PANGAIA product, what did you do with the ***box***?	A. Put it in a trash/rubbish bin B. Put it in a recycle bin C. Put it in backyard compost D. Kept/re-used E. Put it in an industrial compost bin F. Other
3.	After you opened your PANGAIA product, what did you do with the ***film packaging***?	A. Put it in a trash/rubbish bin B. Put it in a recycle bin C. Put it in backyard compost D. Kept/re-used E. Put it in an industrial compost bin F. Other
4.	To the best of your knowledge, which of the following waste management services are ***provided*** by your municipality or are ***available*** to your household? Please select all that apply.	A. Trash/rubbish B. Recycling (separated or mixed) C. Industrial composting D. At-home/backyard composting E. I am not sure
5.	Which of the following waste management services does your household (actually) ***use***? Please select all that apply.[1]	A. At-home/backyard composting B. Trash/rubbish C. Recycling (separated or mixed) D. Industrial composting E. Other
6.	How does your household handle food waste? Please select all that apply.	A. Garbage disposal unit (such as InSinkErator) B. I am not sure C. Drop-off location (for example to a local restaurant or business)

[1] Responses to this question were not analyzed because respondents could have interpreted the question as use in general rather than use specifically in the home.

		D. Backyard/garden compost E. Electric kitchen composter (or a similar device) F. Industrial compost G. Trash/rubbish bin
7.	How do you ***typically*** dispose of a compostable food wrapper?	A. Keep it until I found a compost bin B. Leave it outside to break down C. Keep it until I found a recycle bin D. Put it in a trash/rubbish bin E. Other
8.	Please rank in order what waste disposal method you perceive to be the most environmentally friendly. *Option 1 should be the MOST environmentally friendly, and option 3 should be the LEAST environmentally friendly (in your opinion).*	A. Trash/rubbish (incineration) B. Trash/rubbish (`landfill) C. Compost D. Recycling

To analyze the survey data, we first found the average response time for PANGAIA consumers and non-consumers. Then, we eliminated all responses that did not fall into two standard deviations of each group's average response time. For PANGAIA consumers, three responses were eliminated. For non-consumers, one response was eliminated. We evaluated each survey question individually.

There were several limitations to the way we engaged survey participants. To begin, we recruited our survey respondents by posting on PANGAIA's LinkedIn account. PANGAIA's LinkedIn followers are most likely not representative of the general population because, given their interest in following PANGAIA, these individuals may be more environmentally-minded and invested in proper waste management. This means that the data collected skews towards more 'environmentally-preferred' disposal behaviors (ie: recycling and composting).

Additionally, these more environmentally-minded individuals may be more likely to contribute to the Social Desirability Bias. This bias occurs when respondents give answers to questions that they believe to be 'better' based on a moral judgment, obscuring true opinions or experiences (Krumpal, 2013). Since part of the survey focused on engagement with waste disposal pathways, our survey respondents may have been more likely to falsely claim that they engage with recycling and composting behaviors.

Question #5, which aimed to solicit information on which at-home waste disposal services are used (rather than just available in the home), was excluded from our analysis. We excluded it because respondents could have interpreted the question as use in general rather than use specifically in the home.

Lastly, after eliminating survey respondents that fell outside of two standard deviations from the average survey time, we had 283 responses, 136 of which (48%) came from PANGAIA consumers. This number is too small to be able to generalize to the public. That said, the survey results allow us to have a better understanding of how PANGAIA consumers' access to waste services and waste sorting behaviors compares to the general public. We intended to model end-of-life for each material using data captured by our survey, but due to the low response rate, we elected to use industry data.

5. Results

5.1 LCA Results

5.1.1 Impact Categories

Our analysis focuses on the following impact categories: global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), human toxicity potential, smog formation potential, and ecotoxicity potential. Table 12 contains a description of what each impact category measures and the corresponding units.

Table 12. *The TRACI 2.1 impact categories that we evaluated in our study, a description of each impact category, and the corresponding units (Bare, 2012).*

Impact category	Description	Units
GWP	Represents the heat-trapping capacity of the greenhouse gasses. Important emissions: CO_2 fossil, CH_4, N_2O.	kg CO_2 equivalent (CO_2e)
AP	Quantifies the acidifying effect of substances on their environment. Important emissions: SO_2, NO_x, NH_3, HCl, HF, H_2S.	kg SO_2e
EP	Assesses impacts from an excessive macronutrient load to the environment. Important emissions: NH_3, NO_x, chemical oxygen demand (COD) and biochemical oxygen demand (BOD), N- and P- compounds.	kg N eq

Smog	Determines the formation of reactive substances (e.g. tropospheric ozone) that cause harm to human health and vegetation. Important emissions: NO_x, benzene, toluene, ethylbenzene, xylene (BTEX), non-methane volatile organic compound (NMVOC), CH_4, C_2H_6, C_4H_{10}, C_3H_8, C_6H_{14}, acetylene, Et-OH, formaldehyde.	kg O_3e
Ecotoxicity	Based on a global consensus model which addresses an expanded list of substances that may have potential impacts on ecosystem health.	Clinical trial units (CTU) for ecotoxicity
Human toxicity (cancer and non-cancer)	Based on a global consensus model which addresses an expanded list of substances that may have potential impacts on human health.	CTU for human toxicity

5.1.2 Cradle-to-Gate LDPE Results

Since our model for LDPE is based on an existing, rolled-up dataset in GaBi, our ability to evaluate the impacts from individual unit processes as a segment of the overall life cycle impact is limited. The resolution of our model allows us to view impacts divided into two stages: the cradle-to-gate production of LDPE granulate – from raw material extraction through its production – and the transformation of granulate into a film. We listed LDPE TRACI 2.1 results in Table 13 below, as LDPE is the industry standard for a flexible film bag. The below impacts are scaled according to our reference flow for LDPE (12 g).

Table 13. *Environmental impacts of LDPE production, using TRACI 2.1 impact categories.*

Impact category	**Total**	**Cradle-to-gate granulate production**	**Film transformation**
AP [kg SO_2 eq.]	5.02E-05	4.62E-05	4.00E-06
Ecotoxicity [CTUe]	2.36E-03	2.29E-03	6.45E-05

GWP, excl. biogenic carbon [kg CO_2 eq.]	2.29E-02	2.60E-02	2.95E-03
GWP, incl. biogenic carbon [kg CO_2 eq.]	2.90E-02	2.60E-02	2.95E-03
Human toxicity, cancer [CTUh]	1.44E-11	1.37E-11	6.72E-13
Human toxicity, non-cancer [CTUh]	1.18E-09	1.13E-09	5.49E-11
Smog [kg O_3 eq.]	1.28E-03	1.22E-03	5.74E-05
EP [kg N eq.]	3.49E-06	3.17E-06	3.18E-07

5.1.3 Cradle-to-Gate Algal Flexible Film Results

For the algal flexible film, we modeled different production scenarios using a combination of primary data from algal flexible film producers and secondary data found in literature. Since there is no standardized method of algal flexible film production, we looked at a combination of different steps for our cradle-to-gate models, as seen in Table 14. We set up a baseline model that would have the highest environmental impacts as a ‘worst-case’ scenario, and in each other scenario, we altered one step of the production process from the baseline. The altered factors were: seaweed cultivated or wild harvested; seaweed dried via solar drying, European grid electricity, or natural gas; and inclusion or exclusion of the avoided burden from co-products created during phycocolloid extraction. This allowed us to identify methods that could be used and improved upon to reduce impacts. For our final model, Scenario 6, we changed more than one process to model what an ideal cradle-to-gate process would look like for algal flexible film production to have the lowest environmental impact, or a “best-case” scenario, given currently available technology. The below impacts are scaled according to our reference flow for algal flexible film (18 g).

Table 14. *Different production scenarios and their included steps for algal flexible film production from cradle-to-gate. Scenario 1 lists the baseline model and which steps are included in that process. For Scenarios 2 through 6, the changes made from the baseline are bolded and italicized.*

	Process Steps Included
Scenario 1 (Baseline)	● Seaweed cultivation ● Nutrient uptake and CO_2 sequestration ● Drying using electricity from EU-28 electric grid ● Phycocolloid extraction without avoided burden considered ● Film production
Scenario 2	● ***Wild harvest of seaweed*** ● Nutrient uptake and CO_2 sequestration ● Drying using electricity from EU-28 electric grid ● Phycocolloid extraction without avoided burden considered ● Film production
Scenario 3	● Seaweed cultivation ● Nutrient uptake and CO_2 sequestration ● ***Drying using the sun*** ● Phycocolloid extraction without avoided burden considered ● Film production
Scenario 4	● Seaweed cultivation ● Nutrient uptake and CO_2 sequestration ● ***Drying using natural gas*** ● Phycocolloid extraction without avoided burden considered ● Film production
Scenario 5	● Seaweed cultivation ● Nutrient uptake and CO_2 sequestration ● Drying using electricity from EU-28 electric grid ● ***Phycocolloid extraction with avoided burden considered*** ● Film production
Scenario 6 (best-case scenario)	● ***Wild harvest of seaweed*** ● Nutrient uptake and CO_2 sequestration ● ***Drying using the sun*** ● ***Phycocolloid extraction with avoided burden considered*** ● Film production

Scenario 1 (baseline scenario): Seaweed cultivation, seaweed dried with electricity from the grid, no avoided burden considered.

Table 15. *Environmental impacts of algal film production Scenario #1, using TRACI 2.1 impact categories.*

Impact category	**Total**	**Cultivation**	**Nutrient uptake and CO_2 sequestration**	**Drying**	**Phycocolloid extraction**	**Phycocolloid transport**	**Film production**
AP [kg SO_2 eq.]	4.84E-04	5.00E-05	-	3.04E-04	9.18E-05	9.85E-06	2.86E-05
Ecotoxicity [CTUe]	9.17E-03	3.33E-03	-	3.77E-03	1.22E-03	1.60E-04	6.94E-04
GWP, excl. biogenic carbon [kg CO_2 eq.]	1.77E-01	1.44E-02	-1.60E-02	1.39E-01	3.20E-02	2.04E-03	5.92E-03
GWP, incl. biogenic carbon [kg CO_2 eq.]	1.65E-01	1.44E-02	-1.60E-02	1.39E-01	3.20E-02	2.06E-03	-5.62E-03
Human toxicity, cancer [CTUh]	2.13E-10	7.75E-11	-	6.38E-11	1.76E-11	7.82E-13	5.35E-11
Human toxicity, non-cancer [CTUh]	1.47E-08	6.17E-09	-	5.62E-09	1.33E-09	6.24E-11	1.54E-09
Smog [kg O_3 eq.]	6.79E-03	7.22E-04	-	3.98E-03	1.3E-03	2.27E-04	5.50E-04
EP [kg N eq.]	-2.36E-03	3.76E-06	-2.41E-03	2.92E-05	9.34E-06	9.36E-07	2.99E-06

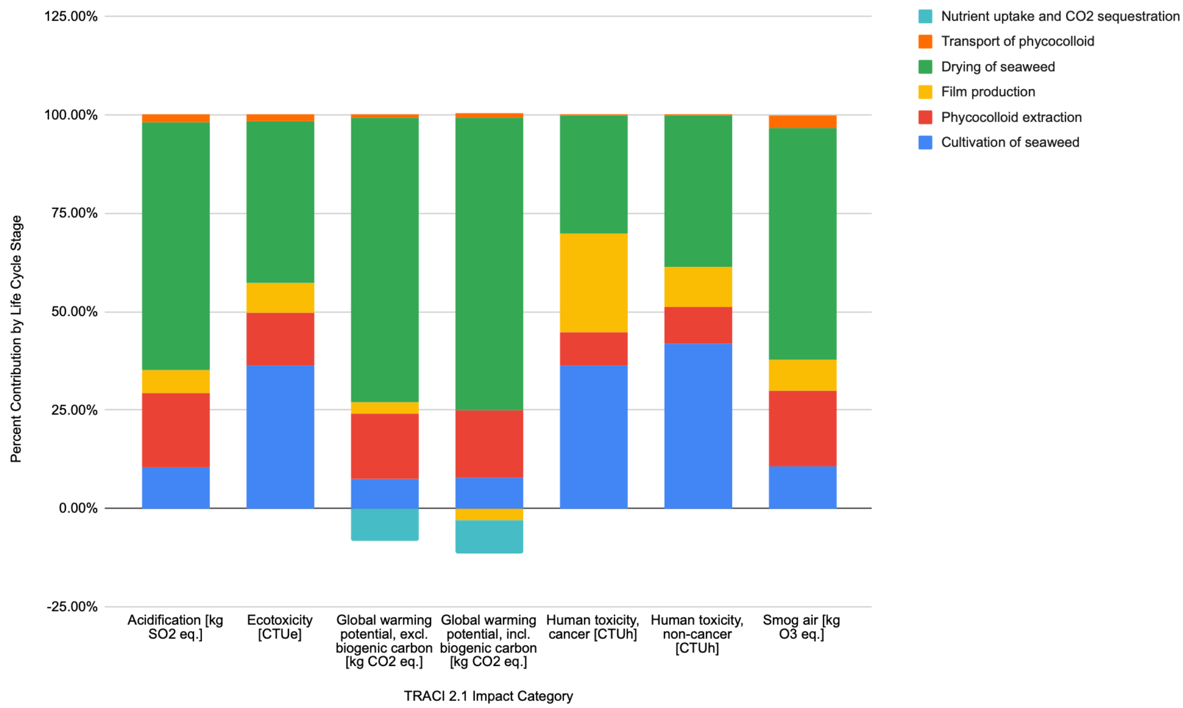

Figure 5. *Contribution analysis of algal flexible film production scenario #1 for TRACI 2.1 impact categories. Refer to Figure 13 for impacts on eutrophication.*

For the baseline model, we selected our processes to include options with the highest environmental impacts. Machine drying powered by electricity has the most significant impact across most impact categories, including acidification, global warming potential, and smog. Seaweed cultivation has large ecotoxicity and human toxicity impacts, while phycocolloid extraction has impacts across all impact categories. Film production's largest impact is on human toxicity. Eutrophication is significantly reduced by seaweed's nutrient sequestration, resulting in the impacts of the other processes being reduced by a factor of nearly 50. Nutrient sequestration also has a small contribution in reducing global warming impacts. These results are for algal flexible film's production "worst case" scenario. The other five scenarios will examine additional ways to reduce the production process impacts.

Scenario 2: Wild-harvested seaweed, seaweed dried with electricity, no avoided burden considered

Table 16. *Environmental impacts of algal flexible film production Scenario #2, using TRACI 2.1 impact categories.*

Impact category	**Total**	**Wild harvest**	**Nutrient uptake and CO_2 sequestration**	**Drying**	**Phycocolloid extraction**	**Phycocolloid transport**	**Film production**
AP [kg SO_2 eq]	4.36E-04	2.53E-06	-	3.04E-04	9.18E-05	9.85E-06	2.86E-05
Ecotoxicity [CTUe]	5.86E-03	2.35E-05	-	3.77E-03	1.22E-03	1.60E-04	6.94E-04
GWP, excl. biogenic carbon [kg CO_2 eq.]	1.63E-01	2.98E-04	-1.60E-02	1.39E-01	3.20E-02	2.04E-03	5.92E-03
GWP, incl. biogenic carbon [kg CO_2 eq.]	1.51E-01	2.86E-04	-1.60E-02	1.39E-01	3.20E-02	2.06E-03	-5.62E-03
Human toxicity, cancer [CTUh]	1.36E-10	1.47E-13	-	6.38E-11	1.76E-11	7.82E-13	5.35E-11
Human toxicity, non-cancer [CTUh]	8.57E-09	2.25E-11	-	5.62E-09	1.33E-09	6.24E-11	1.54E-09
Smog [kg O_3 eq.]	6.15E-03	8.53E-05	-	3.98E-03	1.3E-03	2.27E-04	5.50E-04
EP [kg N eq.]	-2.37E-03	1.72E-07	-2.41E-03	2.92E-05	9.34E-06	9.36E-07	2.99E-06

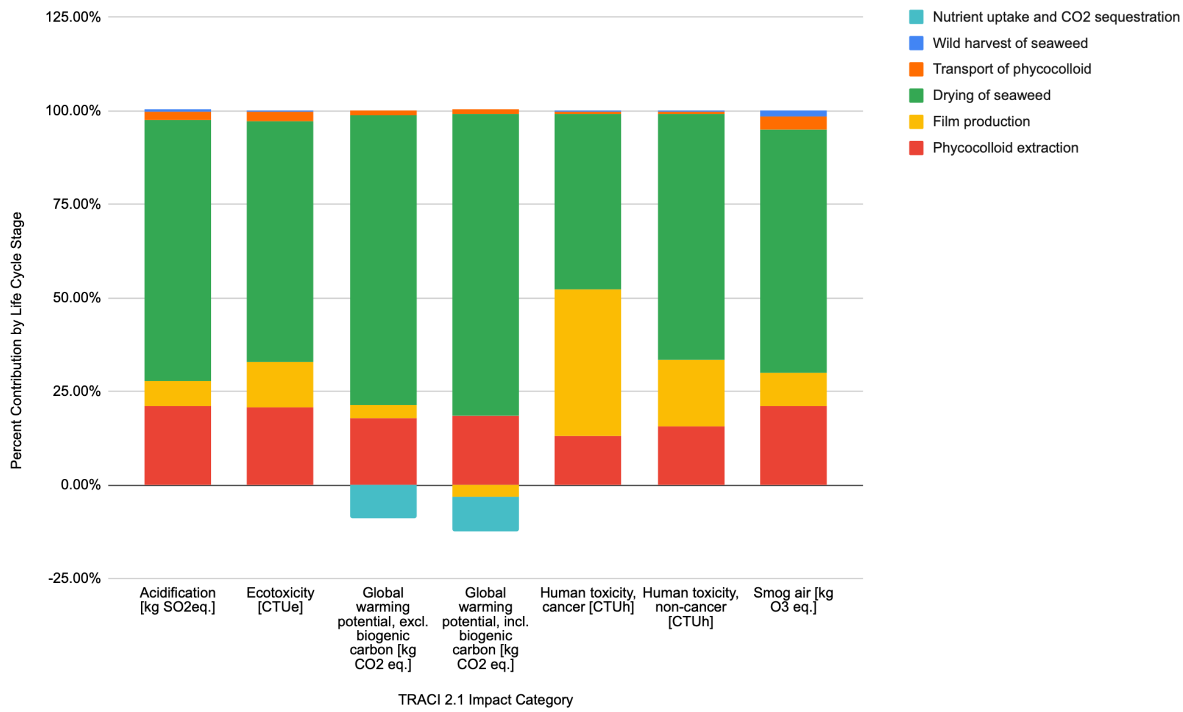

Figure 6. *Contribution analysis of algal film production Scenario #2 for TRACI 2.1 impact categories. Refer to Figure 13 for impacts on eutrophication.*

In this scenario, wild harvest of seaweed occurs instead of cultivation. Wild-harvested seaweed has a significantly lower impact across all impact categories compared to cultivation, as seen in Figure 7 where the blue bar is almost non-existent. It does not require any infrastructure or inputs. This indicates wild-harvested seaweed leads to lower environmental harm. Nonetheless, it is unclear at this time whether wild harvest is a viable option if demand rises. As the cultivation phase already has a relatively small environmental impact, improving cultivation may be a more beneficial choice than switching to wild-harvested seaweed.

Scenario 3: Seaweed cultivation, seaweed dried by the sun, no avoided burden considered

Table 17. *Environmental impacts of algal film production Scenario #3, using TRACI 2.1 impact categories.*

Impact category	**Total**	**Cultivation**	**Nutrient uptake and CO_2 sequestration**	**Phycocolloid extraction**	**Phycocolloid transport**	**Film production**
AP [kg SO_2 eq.]	1.80E-04	5.00E-05	-	9.18E-05	9.85E-06	2.86E-05
Ecotoxicity [CTUe]	5.40E-03	3.33E-03	-	1.22E-03	1.60E-04	6.94E-04

GWP, excl. biogenic carbon [kg CO_2 eq.]	3.80E-03	1.44E-02	-1.60E-02	3.20E-02	2.04E-03	5.92E-03
GWP, incl. biogenic carbon [kg CO_2 eq.]	2.68E-02	1.44E-02	-1.60E-02	3.20E-02	2.06E-03	-5.62E-03
Human toxicity, cancer [CTUh]	1.49E-10	7.75E-11	-	1.76E-11	7.82E-13	5.35E-11
Human toxicity, non-cancer [CTUh]	9.10E-09	6.17E-09	-	1.33E-09	6.24E-11	1.54E-09
Smog [kg O_3 eq.]	2.80E-03	7.22E-04	-	1.3E-03	2.27E-04	5.50E-04
EP [kg N eq.]	-2.39E-03	3.76E-06	-2.41E-03	9.34E-06	9.36E-07	2.99E-06

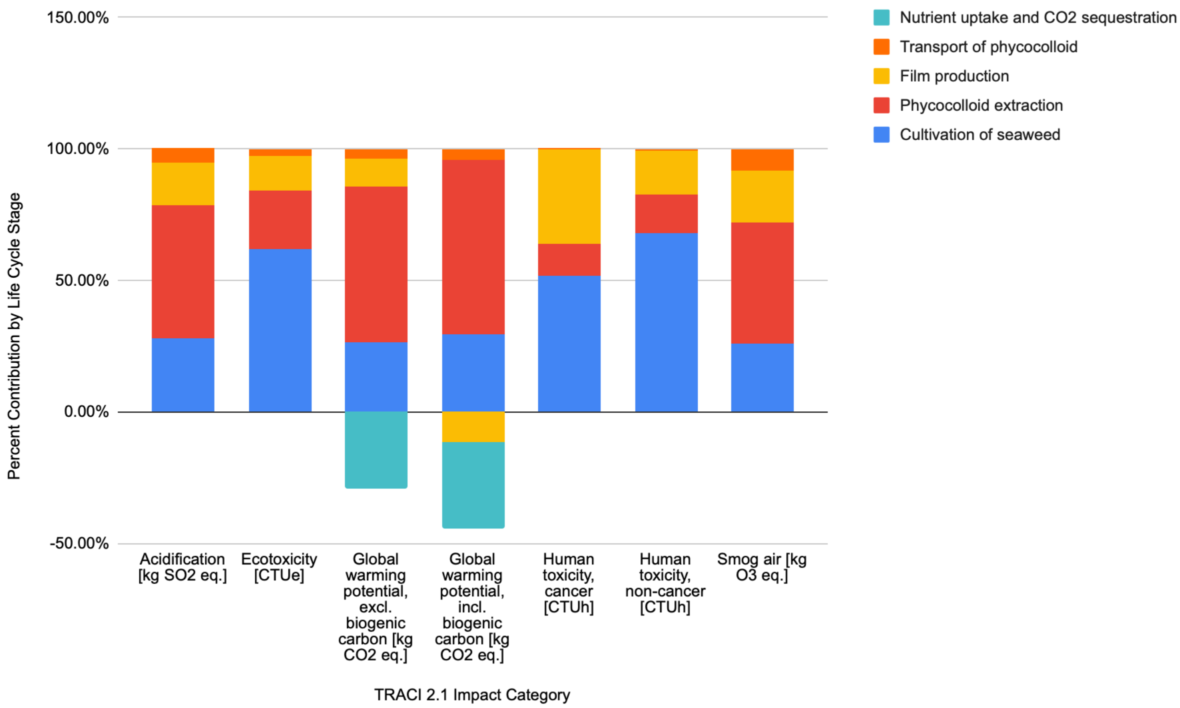

Figure 7. *Contribution analysis of algal flexible film production Scenario #3 for TRACI 2.1 impact categories. Refer to Figure 13 for impacts on eutrophication.*

In Scenario 3, instead of drying the seaweed with electricity, it is sun dried. No environmental impacts result from this method. Since seaweed drying was a significant portion of our baseline scenario's environmental impacts, total environmental impacts across all categories are significantly reduced.

Scenario 4: Seaweed cultivation, seaweed dried with natural gas, no avoided burden considered

Table 18. *Environmental impacts of algal flexible film production Scenario #4, using TRACI 2.1 impact categories.*

Impact category	**Total**	**Cultivation**	**Nutrient uptake and CO_2 sequestration**	**Drying**	**Phycocolloid extraction**	**Phycocolloid transport**	**Film production**
AP [kg SO_2 eq.]	2.27E-04	5.00E-05	-	4.71E-05	9.18E-05	9.85E-06	2.86E-05
Ecotoxicity [CTUe]	6.07E-03	3.33E-03	-	6.66E-04	1.22E-03	1.60E-04	6.94E-04

GWP, excl. biogenic carbon [kg CO_2 eq.]	1.28E-01	1.44E-02	-1.60E-02	8.95E-02	3.20E-02	2.04E-03	5.92E-03
GWP, incl. biogenic carbon [kg CO_2 eq.]	1.16E-01	1.44E-02	-1.60E-02	8.96E-02	3.20E-02	2.06E-03	-5.62E-03
Human toxicity, cancer [CTUh]	1.81E-10	7.75E-11	-	3.13E-11	1.76E-11	7.82E-13	5.35E-11
Human toxicity, non-cancer [CTUh]	1.19E-08	6.17E-09	-	2.82E-09	1.33E-09	6.24E-11	1.54E-09
Smog [kg O_3 eq.]	4.22E-03	7.22E-04	-	1.41E-03	1.3E-03	2.27E-04	5.50E-04
EP [kg N eq.]	-2.39E-03	3.76E-06	-2.41E-03	2.78E-06	9.34E-06	9.36E-07	2.99E-06

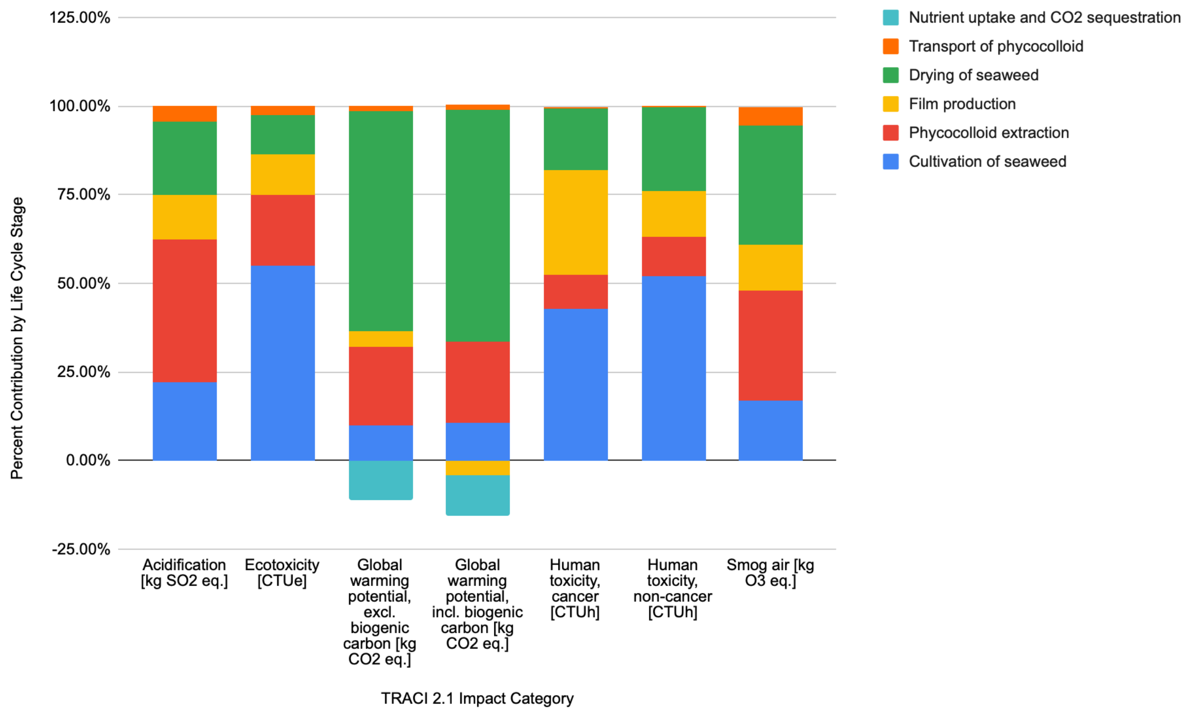

Figure 8. *Contribution analysis of algal film production Scenario #4 for TRACI 2.1 impact categories. Refer to Figure 13 for impacts on eutrophication.*

While Scenario 3 examines sun drying of the seaweed, questions remain about the scalability of this option. In Scenario 4, the seaweed is still machine dried but the source is natural gas instead of electricity. While drying of seaweed still has the most significant global warming impact in this scenario, its contribution is reduced. In other impact categories, its burden is significantly lower than in the baseline model.

Scenario 5: Seaweed cultivation, seaweed dried with electricity from the grid, avoided burden considered

Table 19. *Environmental impacts of algal film production Scenario #5, using TRACI 2.1 impact categories.*

Impact category	**Total**	**Cultivation**	**Nutrient uptake and CO_2 sequestration**	**Drying**	**Phycocolloid extraction**	**Phycocolloid transport**	**Film production**
AP [kg SO_2 eq]	3.78E-04	5.00E-05	-	3.04E-04	-1.41E-05	9.85E-06	2.86E-05
Ecotoxicity [CTUe]	-2.50E-02	3.33E-03	-	3.77E-03	-3.29E-02	1.60E-04	6.94E-04
GWP, excl. biogenic carbon [kg CO_2 eq.]	1.61E-01	1.44E-02	-1.60E-02	1.39E-01	1.63E-02	2.04E-03	5.92E-03
GWP, incl. biogenic carbon [kg CO_2 eq.]	1.59E-01	1.44E-02	-1.60E-02	1.39E-01	2.55E-02	2.06E-03	-5.62E-03
Human toxicity, cancer [CTUh]	2.06E-10	7.75E-11	-	6.38E-11	1.07E-11	7.82E-13	5.35E-11
Human toxicity, non-cancer [CTUh]	1.40E-08	6.17E-09	-	5.62E-09	5.68E-10	6.24E-11	1.54E-09
Smog [kg O_3 eq.]	5.99E-03	7.22E-04	-	3.98E-03	5.07E-04	2.27E-04	5.50E-04
EP [kg N eq.]	-2.37E-03	3.76E-06	-2.41E-03	2.92E-05	2.14E-06	9.36E-07	2.99E-06

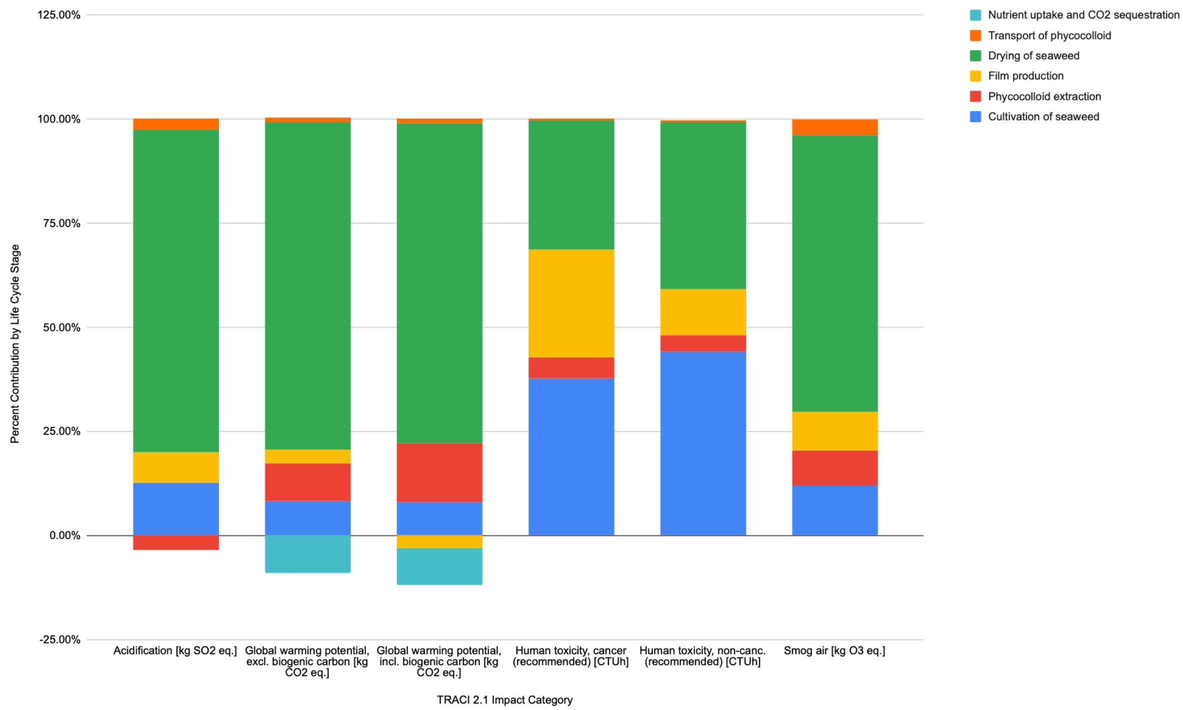

Figure 9. *Contribution analysis of algal flexible film production Scenario #5 for TRACI 2.1 impact categories. Refer to Figure 12 for impacts on ecotoxicity and Figure 13 for impacts on eutrophication.*

In Scenario 5, everything in the baseline is kept the same, but we include the co-products from the phycocolloid extraction step. Using the avoided burden approach described in our methods section, the environmental burden of producing these co-products is avoided and only the impacts of producing the phycocolloid itself are considered. This results in the phycocolloid extraction step having a lower impact across all categories. Ecotoxicity is significantly reduced where the impacts are reduced by over four times. For our avoided burden model, we used data from *Nilsson et al.* (2022) to account for the additional inputs necessary to turn the seaweed by-products into useful co-products. Overall, total environmental impacts are lower when useful co-products are created from phycocolloid extraction and are considered in the modeling.

Scenario 6 (best case): Wild-harvested seaweed, seaweed dried by the sun, avoided burden considered

Table 20. *Environmental impacts of algal flexible film production Scenario #6, using TRACI 2.1 impact categories.*

Impact category	**Total**	**Wild harvest**	**Nutrient uptake and CO_2 sequestration**	**Phycocolloid extraction**	**Phycocolloid transport**	**Film production**
AP [kg SO_2 eq.]	2.69E-05	2.53E-06	-	-1.41E-05	9.85E-06	2.86E-05
Ecotoxicity [CTUe]	-3.20E-02	2.35E-05	-	-3.29E-02	1.60E-04	6.94E-04
GWP, excl. biogenic carbon [kg CO_2 eq.]	8.57E-03	2.99E-04	-1.60E-02	1.63E-02	2.04E-03	5.92E-03
GWP, incl. biogenic carbon [kg CO_2 eq.]	6.18E-03	2.86E-04	-1.60E-02	2.55E-02	2.06E-03	-5.62E-03
Human toxicity, cancer [CTUh]	6.51E-11	1.47E-13	-	1.07E-11	7.82E-13	5.35E-11
Human toxicity, non-cancer [CTUh]	2.19E-09	2.25E-11	-	5.68E-10	6.24E-11	1.54E-09
Smog [kg O_3 eq.]	1.37E-03	8.53E-05	-	5.07E-04	2.27E-04	5.50E-04
EP [kg N eq.]	-2.40E-03	1.72E-07	-2.41E-03	2.14E-06	9.36E-07	2.99E-06

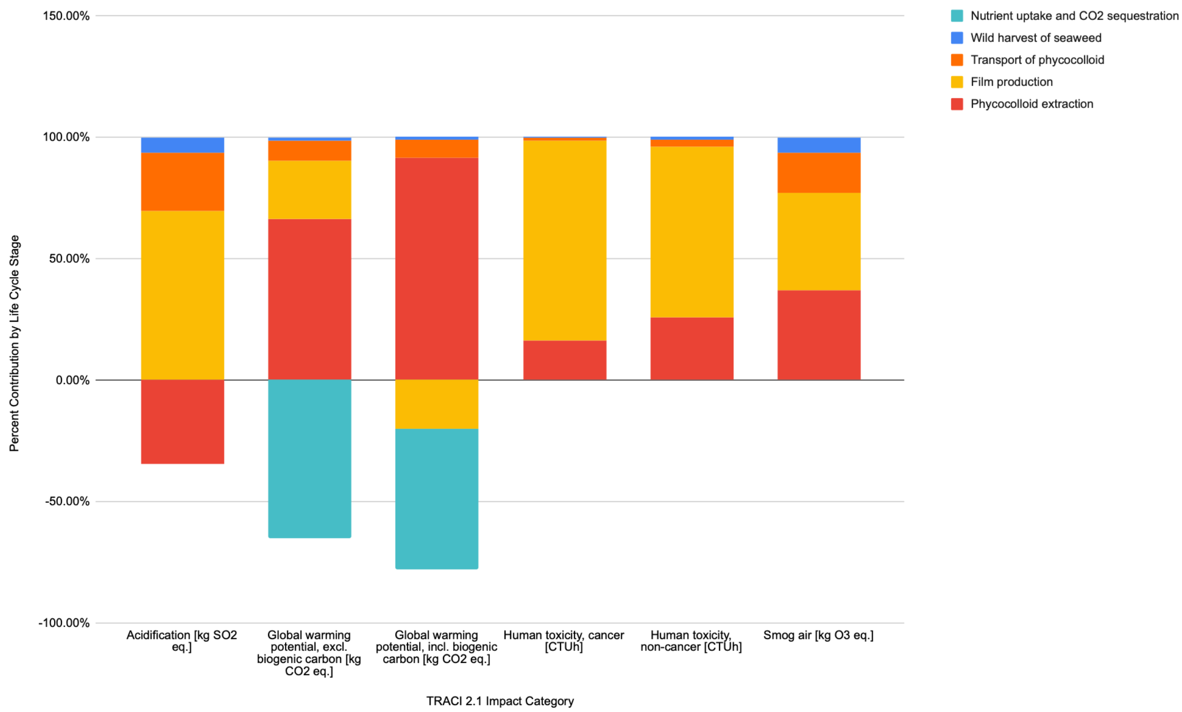

Figure 10. *Contribution analysis of algal film production Scenario #6 for TRACI 2.1 impact categories. Refer to Figure 12 for impacts on ecotoxicity and Figure 13 for impacts on eutrophication.*

This best-case scenario considers which option for the steps of the algal flexible film production would result in the lowest environmental impact. The wild harvest of seaweed, sun drying of seaweed, and inclusion of co-products result in the lowest total environmental impacts of this process.

5.1.4 Scenario Comparison Analysis

Table 21. *Comparison of environmental performance of algal flexible film scenarios to LDPE, using TRACI 2.1 impact categories. LDPE impacts normalized to 1.*

Impact category	LDPE	Scenario 1 (baseline)	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6 (best case)
AP [kg SO_2 eq.]	1.00	9.64	8.69	3.59	4.52	7.53	0.54

Ecotoxicity [CTUe]	1.00	3.89	2.48	2.29	2.57	-10.59	-13.56
GWP, excl. biogenic carbon [kg CO_2 eq.]	1.00	6.10	5.62	1.32	4.41	5.55	0.30
GWP, incl. biogenic carbon [kg CO_2 eq.]	1.00	5.69	5.21	0.92	4.00	5.48	0.21
Human toxicity, cancer [CTUh]	1.00	14.79	9.44	10.35	12.57	14.31	4.52
Human toxicity, non-canc. [CTUh]	1.00	12.46	7.26	7.71	10.08	11.86	1.86
Smog [kg O_3 eq.]	1.00	5.30	4.80	2.19	3.30	4.68	1.07
EP [kg N eq.]	1.00	-676.22	-679.08	-684.81	-684.81	-679.08	-687.68

<u>Acidification</u>

For scenarios where drying is performed with electricity from the grid, this step contributes over 60% of the acidification potential (AP). A switch to natural gas from the electric grid drying reduces the AP from this drying step by 85%.

When switching to sun drying, there are no acidification impacts from the drying step itself. In that case, over half of the AP comes from chemical and electricity use in the phycocolloid extraction step. In a scenario where co-products are avoided, this phycocolloid extraction step has negative AP.

For the best-case scenario, most of the AP comes from the co-substrate that is used in film production. However, there was limited data available for modeling this co-substrate, so impacts may be different from what is found in the model.

Over 90% of LDPE's AP comes from the LDPE granulate production, with the remaining impact stemming from the granulate transformation into film. The LDPE granulate in the GaBi software includes granulate production cradle-to-gate impacts, starting from raw material extraction. However, the software does not provide insight into where the AP occurs in the cradle-to-granulate production process.

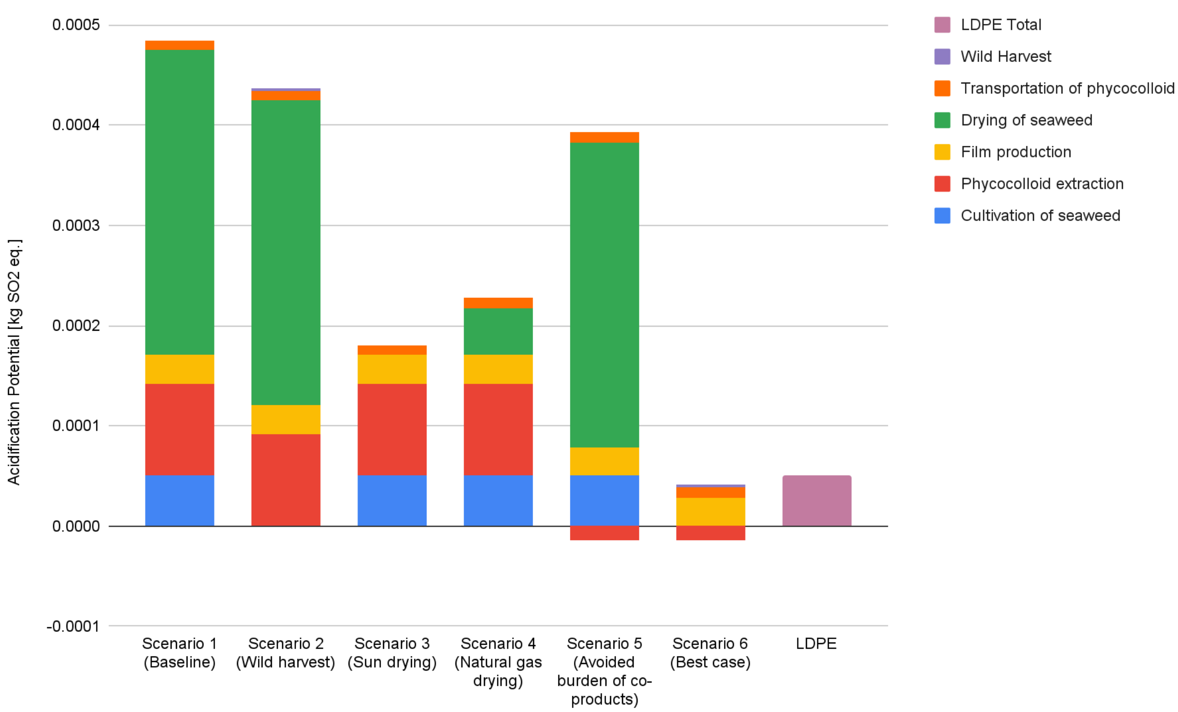

Figure 11. *Acidification scenario comparison.*

Ecotoxicity

Over 75% of all ecotoxicity impacts come from electric grid drying and seaweed cultivation in the baseline scenario. Compared to LDPE, ecotoxicity impacts are greater for the scenarios that include either electric grid drying or seaweed cultivation. For LDPE, granulate production contributes the most to ecotoxicity. We observe major improvements when accounting for co-products' avoided burden in the phycocolloid extraction step, resulting in a nearly 450% reduction relative to the baseline. The ecotoxicity of the avoided production is larger than the ecotoxicity of the cradle-to-gate production of the seaweed flexible film. Thus, avoiding the creation of co-products more than offsets the ecotoxicity impacts, making the overall ecotoxicity impact a negative value.

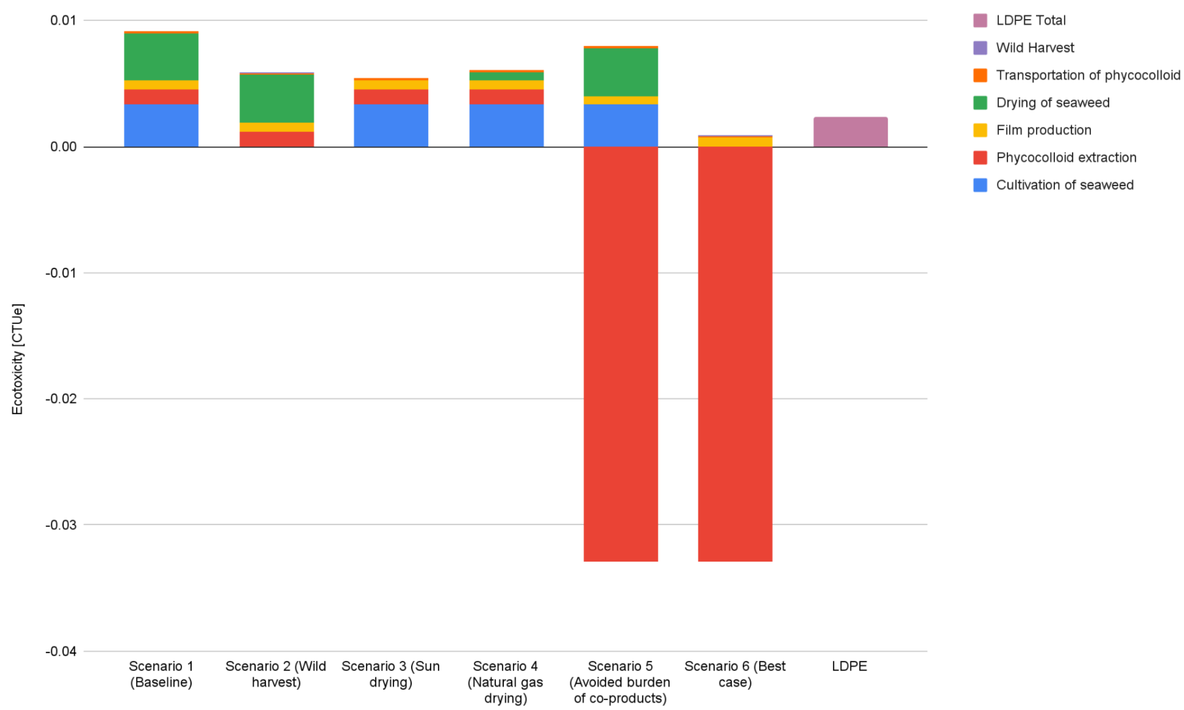

Figure 12. *Ecotoxicity scenario comparison.*

<u>Eutrophication</u>

Our algal flexible film production scenarios significantly outperform LDPE for this impact category. Because eutrophication mitigation from nutrient uptake far outweighs the eutrophication potential generated during film production, the seaweed film scenarios have roughly equivalent negative eutrophication potentials. However, there is nearly a 700-time decrease in eutrophication potential for all seaweed film scenarios when compared to LDPE.

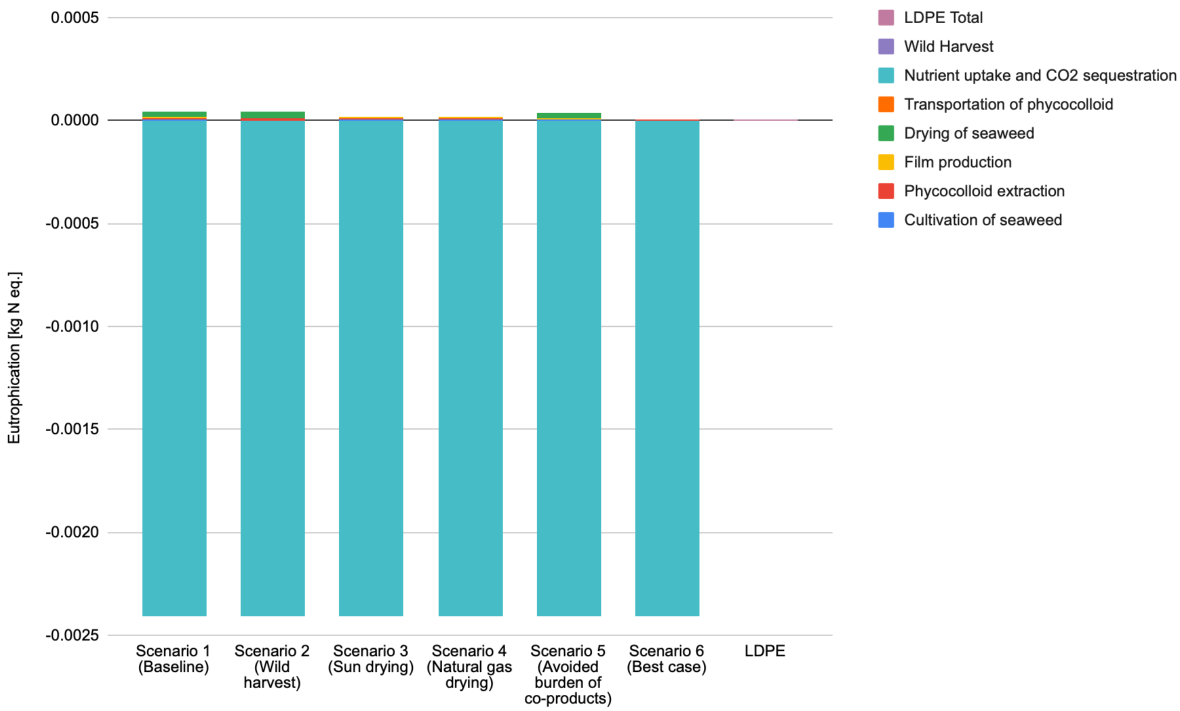

Figure 13. *Eutrophication scenario comparison.*

<u>Global Warming Potential (excluding and including biogenic carbon)</u>

For all scenarios using active drying methods, the drying step significantly contributes to global warming potential (GWP). Roughly 80% of GWP results from the electricity used in seaweed drying. Drying seaweed using natural gas reduces the GWP by 35% compared to electric drying.

When sun drying is used, the phycocolloid extraction step contributes the most to GWP, around 83%. In this extraction step, 60% of the GWP results from the electricity used in this process. The scenarios that use sun drying are competitive with or even better than LDPE for GWP.

All impacts when including biogenic carbon are slightly lower than those excluding biogenic carbon. This is due to the co-substrate used in film production, which noted earlier may have different impacts than what is seen from our model due to limited data availability. When including biogenic carbon, Scenario 3's GWP is lower than that of LDPE, while excluding biogenic carbon results in GWP being slightly higher than that of LDPE.

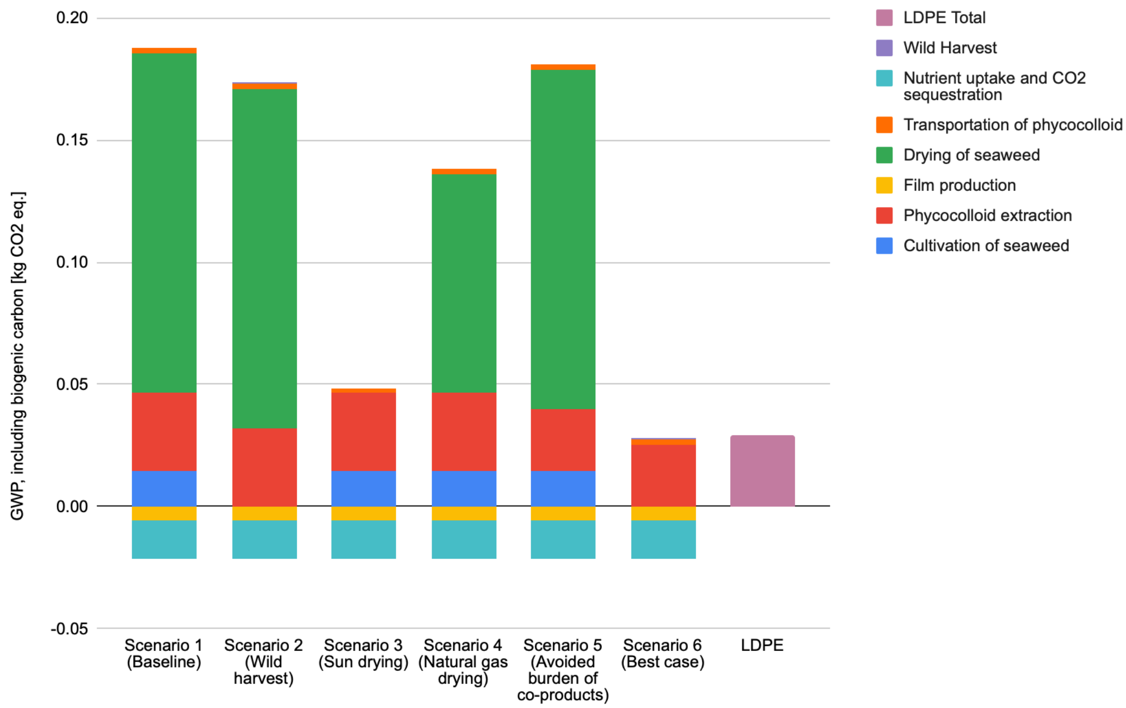

Figure 14. *GWP including (incl.) biogenic carbon scenario comparison.*

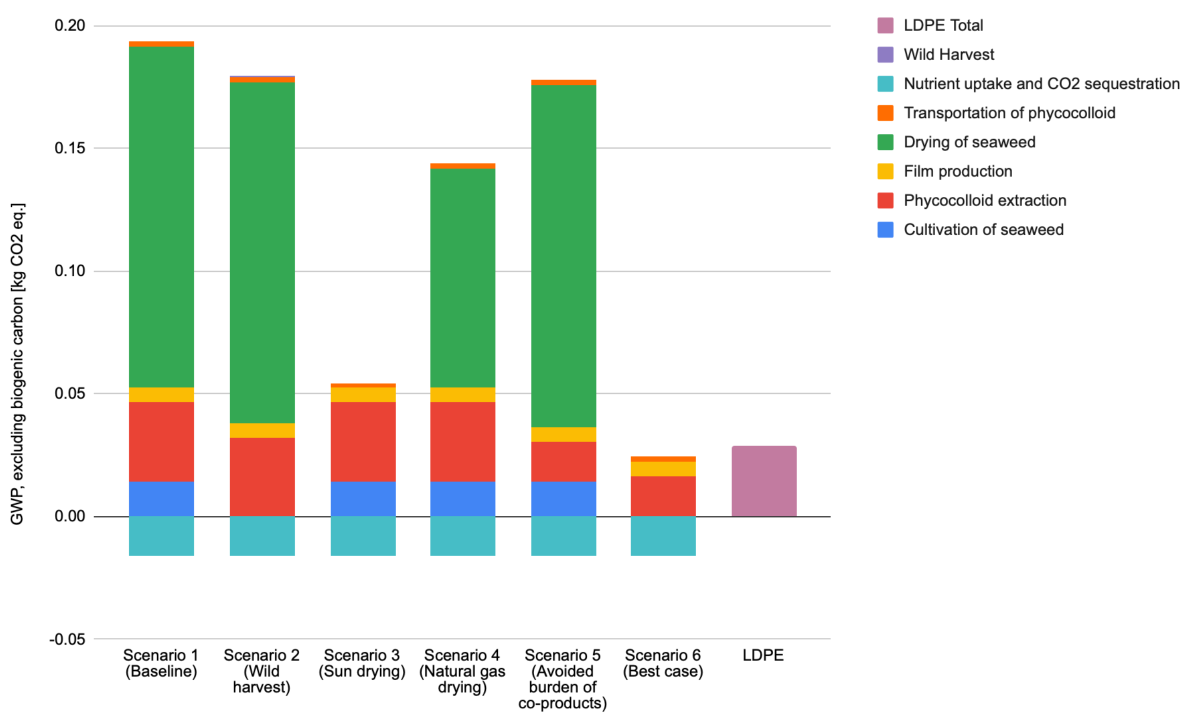

Figure 15. *GWP excluding (excl.) biogenic carbon scenario comparison.*

Human toxicity (cancer and non-cancer)

Film production accounts for roughly 25% of total human toxicity impacts, predominantly resulting from the aforementioned co-substrate use.

For scenarios where seaweed is cultivated, 36% of all human toxicity potential stems from this step. PET fibers and stainless steel used in cultivation infrastructure each account for roughly a third of the step's impacts.

Drying with grid electricity also contributes roughly 30% of the total human toxicity potential. The toxicity potential from drying is decreased by 50% when natural gas is used in place of grid electricity, reducing the overall potential by 15% compared to the baseline.

Sources of impacts for each scenario, as well as the relative impacts between scenarios, are similar for both types of human toxicity (cancer and non-cancer potential). However, the potential impact from cancer-causing toxicities is roughly 100 times smaller than the potential impact from non-cancer-causing toxicities. In all cases, LDPE outperforms seaweed.

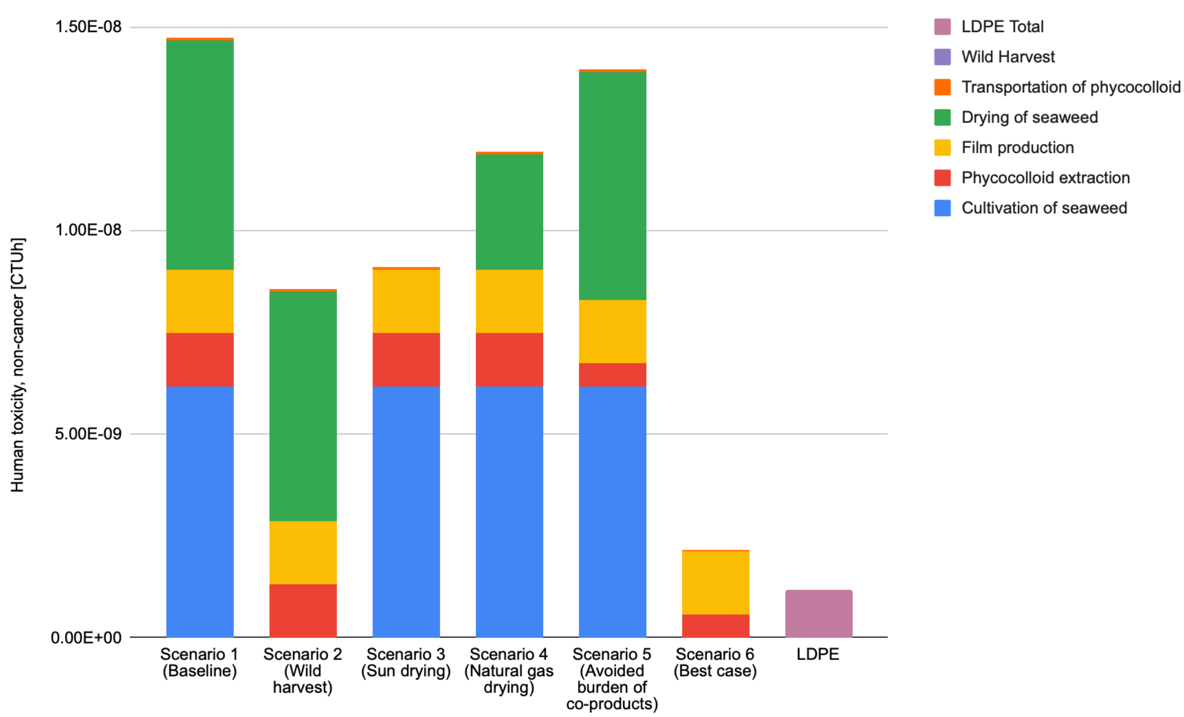

Figure 16. *Human toxicity, non-cancer scenario comparison.*

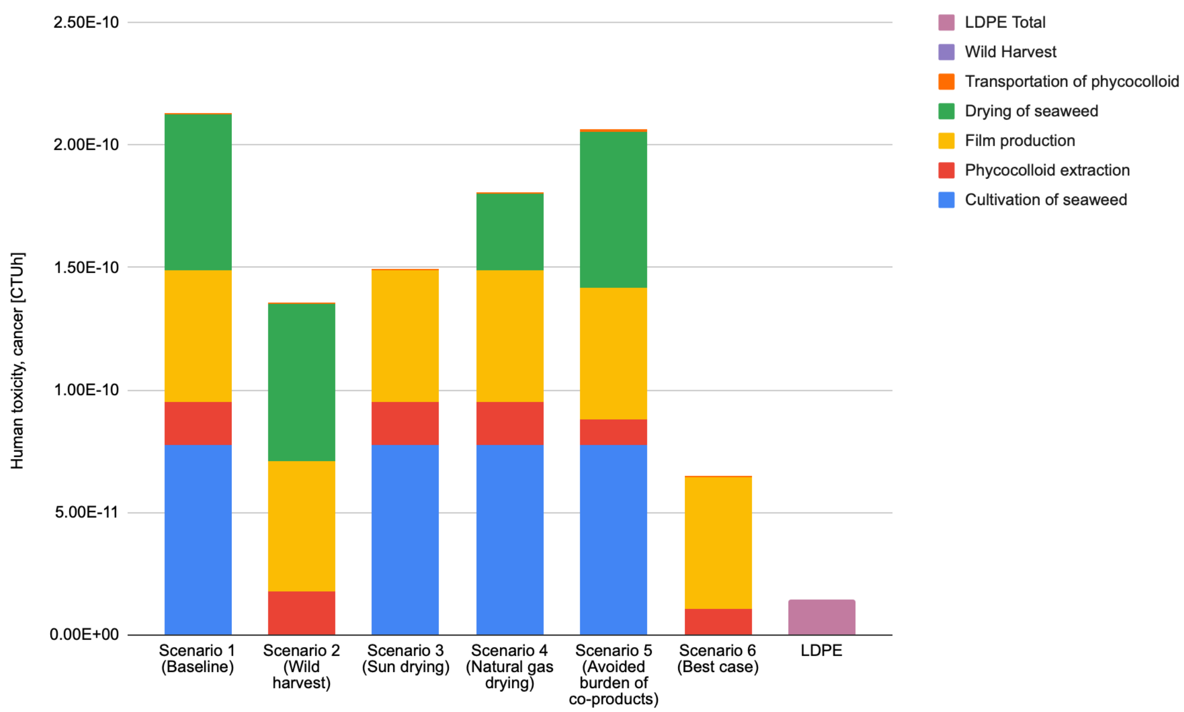

Figure 17. *Human toxicity, cancer scenario comparison.*

Smog Air

As is the case with many impact categories, electricity for drying accounts for roughly 60% of seaweed flexible film's production impact. Switching to natural gas drying reduced the impacts of this step by nearly 65% and the total production impacts by 40%. Meanwhile, sun drying reduced smog's total impacts by 60% against the baseline.

Although wild-harvested seaweed outperforms cultivation, the contributions from seaweed cultivation are minimal to smog formation. Again, the majority of this step stems from the use of stainless steel in the offshore farm infrastructure.

Modeling the avoided burden from the useful co-products created from the algae processing step reduces impacts by 61% for this unit process. In this impact category, LDPE outperforms every seaweed film production scenario, with our best-case scenario having a 7% greater impact than LDPE.

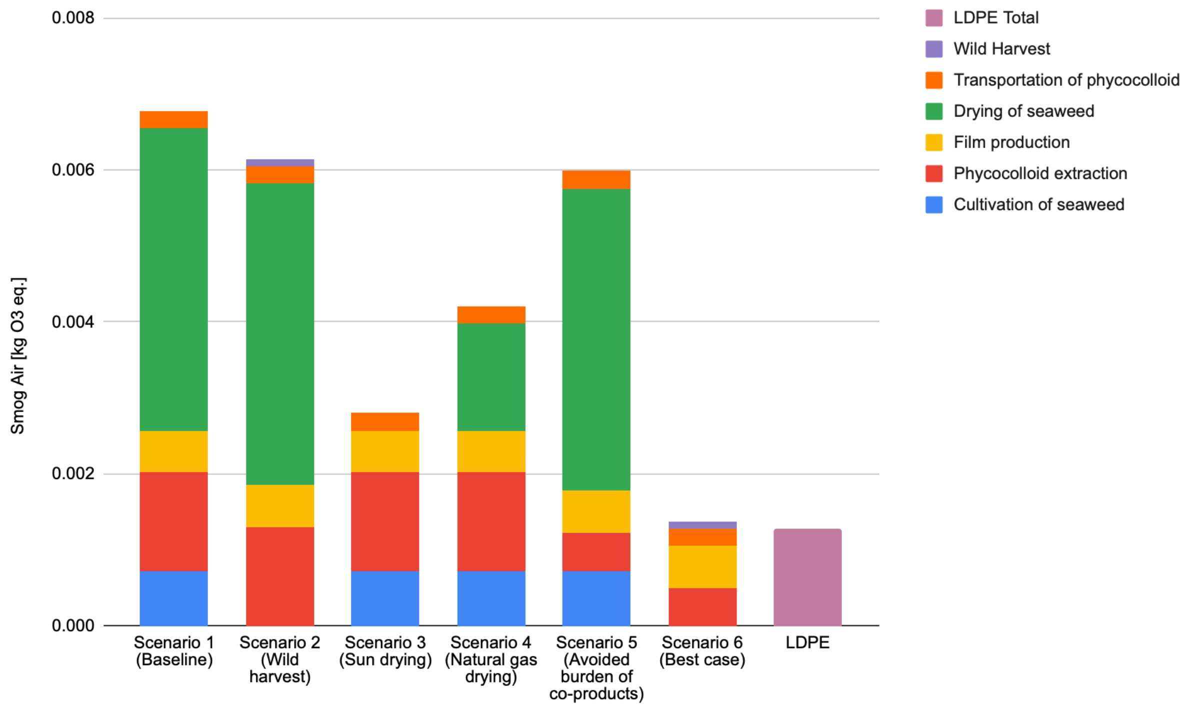

Figure 18. *Smog air scenario comparison.*

5.1.5 Geographical Comparison

In the baseline scenario described above, we selected all energy processes from European Union energy production. For our geographical region comparison, we changed the location for processes in our baseline scenario – to North America and South Asia – to explore how using electricity grids from different countries (thus with different proportions of coal, natural gas, renewables, etc.) would affect the impacts. We separated these changes from our different scenarios above because companies may have less control over where different production steps occur. Nonetheless, we wanted to examine if there were any significant differences between different regions. In all impact categories, the North American grid mix outperformed the South Asian grid mix.

North America

Table 22. *Environmental impacts of the algal film production baseline scenario using TRACI 2.1 impact categories and with North America as the location of production.*

Impact category	Total	Cultivation	Nutrient sequestration	Drying	Phycocolloid extraction	Phycocolloid transport	Film production
AP [kg SO_2 eq.]	4.64E-04	4.94E-05	-	2.69E-04	8.52E-05	3.18E-05	2.85E-05
Ecotoxicity [CTUe]	9.62E-03	3.34E-03	-	4.16E-03	1.36E-03	7.90E-05	6.74E-04
GWP, excl. biogenic carbon [kg CO_2 eq.]	2.38E-01	1.52E-02	-1.60E-02	1.91E-01	4.11E-02	1.04E-03	5.94E-03
GWP, incl. biogenic carbon [kg CO_2 eq.]	2.26E-01	1.52E-02	-1.60E-02	1.91E-01	4.10E-02	1.00E-03	-5.60E-03
Human toxicity, cancer [CTUh]	1.90E-10	7.72E-11	-	4.38E-11	1.56E-11	3.86E-13	5.31E-11
Human toxicity, non-cancer [CTUh]	1.26E-08	6.15E-09	-	3.61E-09	1.33E-09	3.08E-11	1.53E-09
Smog [kg O_3 eq.]	6.79E-03	7.06E-04	-	3.80E-03	1.10E-03	6.32E-04	5.49E-04
EP [kg N eq.]	-2.37E-03	3.75E-06	-2.41E-03	2.14E-05	8.95E-06	1.28E-06	2.93E-06

South Asia

Table 23. *Environmental impacts of the algal flexible film production baseline scenario using TRACI 2.1 impact categories and with South Asia as the location of production.*

Impact category	Total	Cultivation	Nutrient sequestration	Drying	Phycocolloid extraction	Phycocolloid transport	Film production
AP [kg SO_2 eq.]	5.54E-03	1.08E-04	-	4.63E-03	7.81E-04	1.70E-07	2.96E-05
Ecotoxicity [CTUe]	3.03E-02	3.57E-03	-	2.19E-02	4.17E-03	1.02E-06	6.98E-04
GWP, excl. biogenic carbon [kg CO_2 eq.]	5.00E-01	1.82E-02	-1.60E-02	4.15E-01	7.68E-02	2.75E-05	0.0060
GWP, incl. biogenic carbon [kg CO_2 eq.]	4.88E-01	1.82E-02	-1.60E-02	4.15E-01	7.68E-02	2.87E-05	-0.0056
Human toxicity, cancer [CTUh]	3.64E-10	7.91E-11	-	1.92E-10	3.92E-11	5.31E-15	5.35E-11
Human toxicity, non-cancer [CTUh]	4.62E-08	6.52E-09	-	3.23E-08	5.87E-09	4.57E-13	1.55E-09
Smog [kg O_3 eq.]	4.55E-02	1.15E-03	-	3.73E-02	6.46E-03	4.14E-06	5.57E-04
EP [kg N eq.]	-2.27E-03	4.85E-06	-2.41E-03	1.07E-04	2.26E-05	9.88E-09	3.01E-06

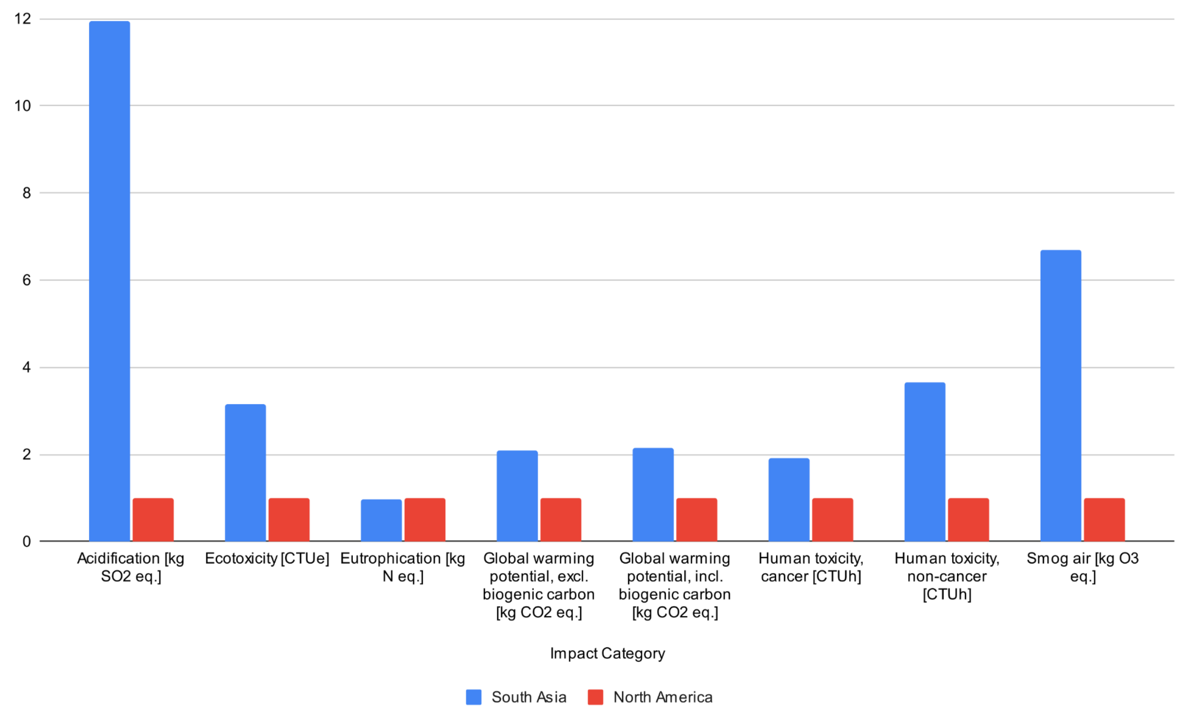

Figure 19. *A geographical comparison of algal film production's environmental impacts in North America and South Asia. The impacts of the North American model are normalized to 1.*

5.1.6 End-of-Life

Our end-of-life models use data from the EPA to account for different disposal pathways for each material. Due to a minimal amount of available data for our algal flexible film's disposal methods and the lack of background data built into GaBi, the uncertainty surrounding these results are much larger than our cradle-to-gate results. Therefore, we decided to keep these separate from the production models and to briefly highlight the impacts while calling for more research into consumer-material interactions and disposed algal flexible film behavior.

Both materials' global warming potentials are impacted massively by incineration, as their high carbon contents release CO_2 when burned. However, this phase generates electricity, which we are able to model as an avoided burden. Accounting for this avoided burden in the model lowers overall GWP. Meanwhile, landfill attributes nearly all (~99%) of the environmental impacts for human toxicity (cancer and non-cancer), smog air, eutrophication, and ecotoxicity. Since we used background data for landfilled plastic waste for both materials, emissions profiles are very similar, with differences stemming only from the amount of material entering the waste stream. It is unclear how exactly this would change with more accurate models. For smog air, reductions for the avoided burden of electricity provide modest reductions to overall emissions. Impacts for acidification stem mostly from landfill and incineration, with a reduction (~30-45%) from the avoided burden of electricity.

Figure 23 and Table 25 below show the relative impacts from cradle-to-gate processing and end-of-life for LDPE and seaweed flexible film, respectively. Generally, a material's end-of-life behavior does not contribute significantly to its cradle-to-grave life cycle impacts.

For LDPE, eutrophication potential is only 1.27 times higher than its end-of-life cradle-to-gate impacts. Nonetheless, for all other impact categories, cradle-to-gate impacts vary from 3-55 times higher than those from end-of-life.

For all impact categories except EP, Scenario 1's cradle-to-gate impacts are larger than end-of-life impacts. Scenario 6's cradle-to-gate impacts also exceed end-of-life impacts for all categories except EP and ecotoxicity, but the differences between the two life phases are much smaller because the cradle-to-gate impacts are so optimized in this scenario. Because Scenario 6 accounts for avoided burden from phycocolloid extraction co-products, which makes its ecotoxicity potential negative, end-of-life impacts are greater than cradle-to-gate. Similarly, because both scenarios model nitrogen and phosphorus uptake and end-of-life processing releases nutrients, the impacts to eutrophication potential are larger for end-of-life.

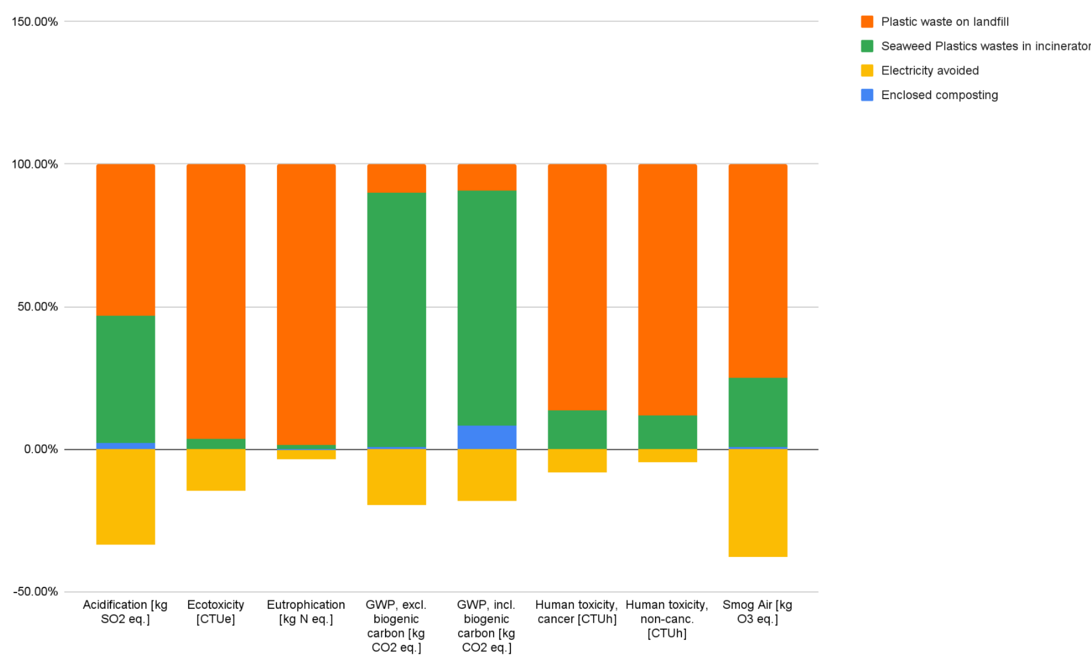

Figure 20. *Algal flexible film end-of-life model.*

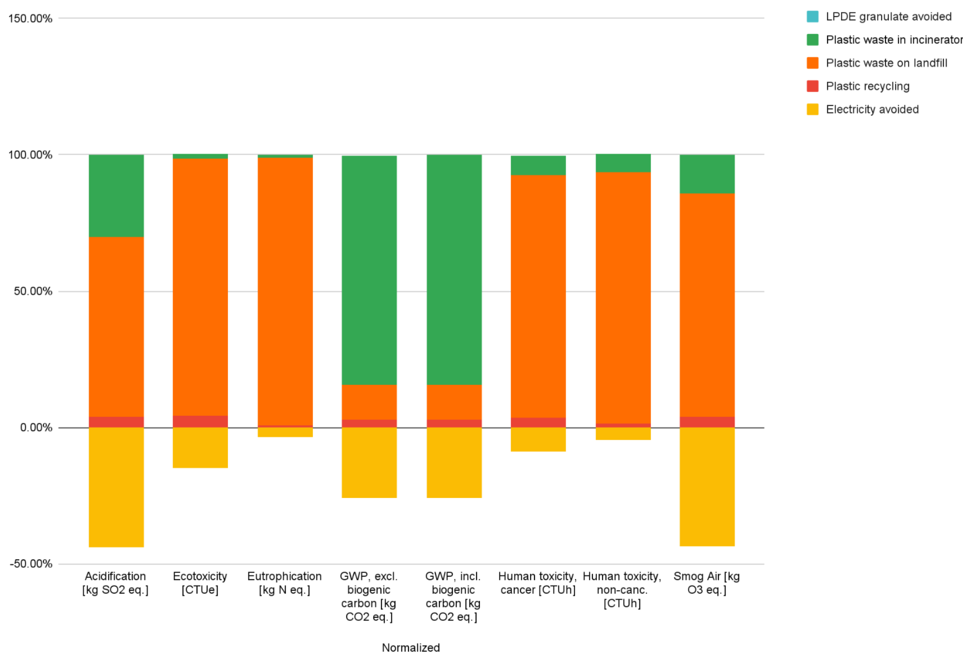

Figure 21. *LDPE end-of-life model.*

Table 24. *LDPE and algal flexible film end-of-life impacts comparison.*

Impact category	**LDPE total**	**Algal flexible film total**
AP [kg SO_2 eq.]	1.64E-06	3.21E-06
Ecotoxicity [CTUe]	1.15E-04	1.48E-04
GWP, excl. biogenic carbon [kg CO_2 eq.]	2.59E-03	4.71E-03
GWP, incl. biogenic carbon [kg CO_2 eq.]	2.59E-03	5.18E-03
Human toxicity, cancer [CTUh]	2.17E-12	2.97E-12
Human toxicity, non-canc. [CTUh]	3.46E-10	4.80E-10
Smog [kg O_3 eq.]	2.35E-05	3.74E-05
EP [kg N eq.]	2.75E-06	3.64E-06

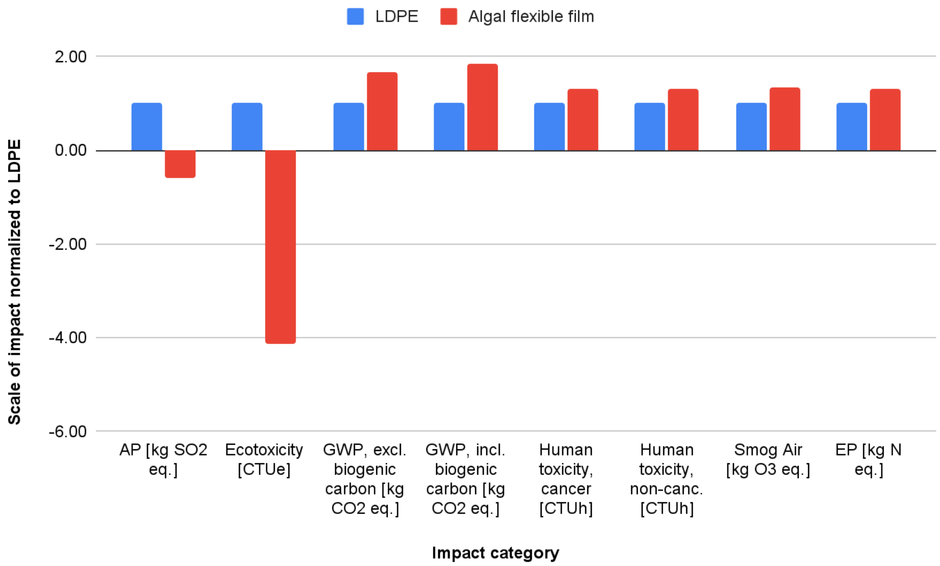

Figure 22. *End-of-life impacts for LDPE and algal flexible film, with LDPE normalized to 1.*

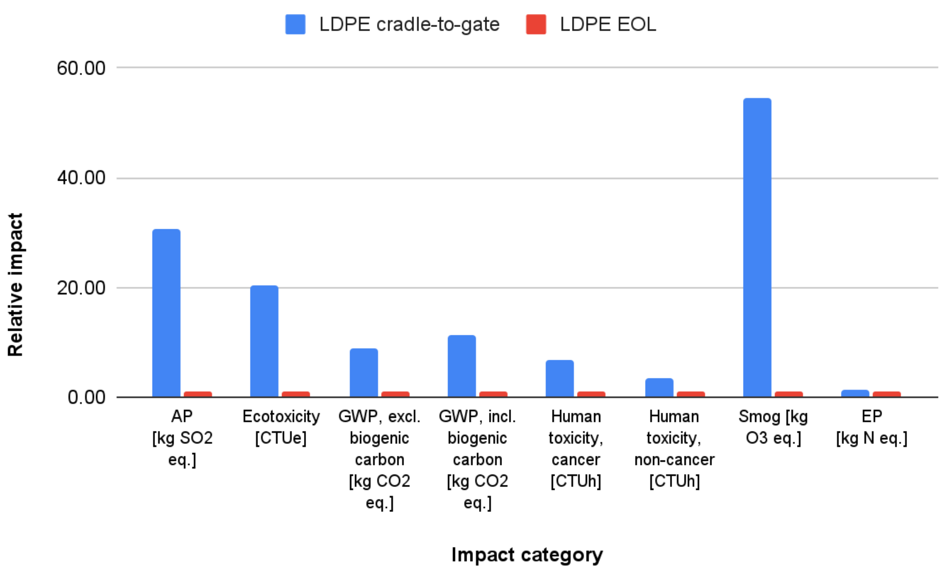

Figure 23. *LDPE end-of-life (EOL) impacts relative to LDPE cradle-to-gate impacts, with LDPE EOL normalized to 1.*

Table 25. *Algal flexible film end-of-life (EOL) impacts relative to Scenarios #1 and #6 cradle-to-gate impacts, with algal flexible film EOL normalized to 1.*

Impact category	Scenario 1 cradle-to-gate	Scenario 6 cradle-to-gate	Algal flexible film EOL
AP [kg SO2 eq.]	150.78	8.38	1.00
Ecotoxicity [CTUe]	61.96	-216.22	1.00

GWP, excl. biogenic carbon [kg CO2 eq.]	37.58	1.82	1.00
GWP, incl. biogenic carbon [kg CO2 eq.]	31.85	1.19	1.00
Human toxicity, cancer [CTUh]	71.72	21.92	1.00
Human toxicity, non-cancer [CTUh]	30.63	4.56	1.00
Smog [kg O3 eq.]	181.55	36.63	1.00
EP [kg N eq.]	-648.35	-659.34	1.00

5.2 Survey Results

We collected 283 survey responses and sorted respondents in two categories: PANGAIA consumers and non-consumers. There were 136 PANGAIA consumers and 147 non-consumers. Below are tables that show how survey respondents answered each question.

Table 26. *Response breakdown to the question, "Have you bought a PANGAIA product before?" The first column lists the answer options (yes and no). The second column is the number of yes responses and the number of no responses, and the third column is the corresponding percentage to the number of yes and no responses.*

Answer options	Number of responses	Percentage of responses
Yes	136	48%
No	147	52%

Table 27. *Response breakdown to the question, "After you opened your PANGAIA product, what did you do with the box?" This question was only given to survey respondents who answered they had bought a product before. The first column lists the waste disposal methods. The second column is the number of PANGAIA consumer responses, and the third column is the corresponding percentage of PANGAIA consumer responses.*

Waste disposal methods	Number of PANGAIA consumer responses	Percentage of PANGAIA consumer responses
Kept/re-used	22	16.2%
Put it in a recycle bin	88	64.7%
Put it in a trash/rubbish bin	9	6.6%
Put it in an industrial compost bin	8	5.9%

Put it in backyard compost	9	6.6%

Table 28. *Response breakdown to the question, "After you opened your PANGAIA product, what did you do with the film packaging?" This question was only given to survey respondents who answered they had bought a PANGAIA product before. The first column lists the waste disposal methods. The second column is the number of PANGAIA consumer responses, and the third column is the corresponding percentage of PANGAIA consumer responses.*

Waste disposal methods	Number of PANGAIA consumer responses	Percentage of PANGAIA consumer responses
Kept/re-used	21	15.4%
Put it in a recycle bin	29	21.3%
Put it in a trash/rubbish bin	48	35.3%
Put it in an industrial compost bin	17	12.5%
Put it in backyard compost	21	15.4%

Table 29. *Response breakdown to the question, "To the best of your knowledge, which of the following waste management services are provided by your municipality or are available to your household? Please select all that apply." The first column lists the available household waste management services or options. The second column is the number of PANGAIA consumer responses. The third column is the corresponding percentage of PANGAIA consumer responses. The fourth column is the number of non-consumer responses, and the fifth column is the corresponding percentage of non-consumer responses.*

Available household waste management services or options	Number of PANGAIA consumer responses	Percentage of PANGAIA consumer responses	Number of non-consumer responses	Percentage of non-consumer responses
Only has trash	11	8.1%	0	3.9%
Has trash and recycling	110	80.9%	132	85.5%
Has industrial compost	40	29.4%	37	27.2%
Has at-home/backyard compost	38	27.9%	47	30.0%
Has industrial or at-home/backyard compost	63	46.3%	73	48.1%

Has recycling and some form of compost (industrial or at-home/backyard)	51	37.5%	65	41.0%
I am not sure	9	6.6%	1	3.5%

We decided to abandon the survey question, "Which of the following waste management services does your household (actually) *use*? Please select all that apply." Responses to this question were not analyzed because respondents may have interpreted the question in two different ways: use within the household or use in general. Since the question could have been interpreted in two ways, we are not able to draw any conclusions for either interpretation because we do not know the breakdown of how respondents interpreted the question.

Table 30. *Response breakdown to the question, "How does your household handle food waste? Please select all that apply." The first column lists the household food waste disposal methods. The second column is the number of PANGAIA consumer responses. The third column is the corresponding percentage of PANGAIA consumer responses. The fourth column is the number of non-consumer responses, and the fifth column is the corresponding percentage of non-consumer responses.*

Household food waste disposal methods	**Number of PANGAIA consumer responses**	**Percentage of PANGAIA consumer responses**	**Number of non-consumer responses**	**Percentage of non-consumer responses**
Just trash/rubbish	51	37.5%	55	37.4%
Just industrial compost	15	11.0%	18	12.2%
Just backyard/garden compost	14	10.3%	13	8.8%
Just electric kitchen device	3	2.2%	1	0.7%
Just garbage disposal	6	4.4%	3	2.0%
Just drop off location	0	0.0%	4	2.7%
Includes industrial compost or backyard/garden compost or electric kitchen device or drop off location	80	58.8%	62	42.2%

Just industrial compost or backyard/garden compost or electric kitchen device or drop off location (does not include trash)	49	36.0%	41	27.9%
I am not sure	5	3.7%	4	2.7%

Table 31. *Response breakdown to the question, "How do you typically dispose of a compostable food wrapper?" The first column lists the compostable food wrapper disposal methods. The second column is the number of PANGAIA consumer responses. The third column is the corresponding percentage of PANGAIA consumer responses. The fourth column is the number of non-consumer responses, and the fifth column is the corresponding percentage of non-consumer responses.*

Compostable food wrapper disposal methods	Number of PANGAIA consumer responses	Percentage of PANGAIA consumer responses	Number of non-consumer responses	Percentage of non-consumer responses
Keep it until I found a compost bin	35	25.9%	40	27.2%
Keep it until I found a recycle bin	20	14.8%	20	13.6%
Leave it outside to break down	5	3.7%	3	2.0%
Put it in a trash/rubbish bin	70	51.9%	84	57.1%

Table 32. *Response breakdown to the question, "Please rank in order what waste disposal method you perceive to be the most environmentally friendly." The first column lists the rankings for disposal methods based on environmentally friendliness from most environmentally friendly (1) to least environmentally friendly (4). The second column is the number of PANGAIA consumer and non-consumer responses, and the third column is the corresponding percentage of PANGAIA consumer and non-consumer responses.*

Perceived ranking of the most environmentally friendly disposal methods	Number of PANGAIA consumer and non-consumer responses	Percentage of PANGAIA consumer and non-consumer responses
Compost (1); Recycling (2); Incineration (3); Landfill (4)	119	42.1%

Compost (1); Recycling (2); Landfill (3); Incineration (4)	68	24.0%
Recycling (1); Compost (2); Incineration (3); Landfill (4)	32	11.3%
Recycling (1); Compost (2); Landfill (3); Incineration (4)	20	7.1%
Compost (1); Incineration (2); Recycling (3); Landfill (4)	19	6.7%
Recycling (1); Incineration (2); Compost (3); Landfill (4)	5	1.8%
Compost (1); Landfill (2); Incineration (3); Recycling (4)	3	1.1%
Compost (1); Landfill (2); Recycling (3); Incineration (4)	3	1.1%
Incineration (1); Compost (2); Recycling (3); Landfill (4)	2	0.7%
Recycling (1); Incineration (2); Landfill (3); Compost (4)	2	0.7%
Incineration (1); Landfill (2); Recycling (3); Compost (4)	2	0.7%
Landfill (1); Recycling (2); Compost (3); Incineration (4)	2	0.7%
Landfill (1); Recycling (2); Incineration (3); Compost (4)	2	0.7%
Recycling (1); Landfill (2); Incineration (3); Compost (4)	1	0.4%
Incineration (1); Landfill (2); Compost (3); Recycling (4)	1	0.4%
Landfill (1); Compost (2); Recycling (3); Incineration (4)	1	0.4%
Landfill (1); Incineration (2); Recycling (3); Compost (4)	1	0.4%

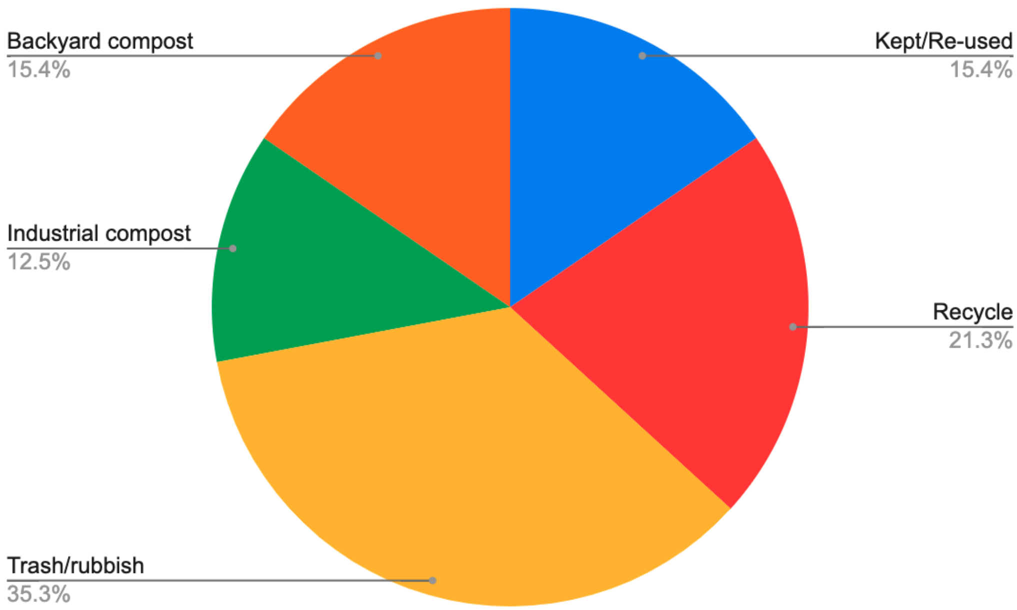

Figure 24. *Breakdown of how PANGAIA consumer survey respondents disposed of the compostable film packaging after opening their PANGAIA product.*

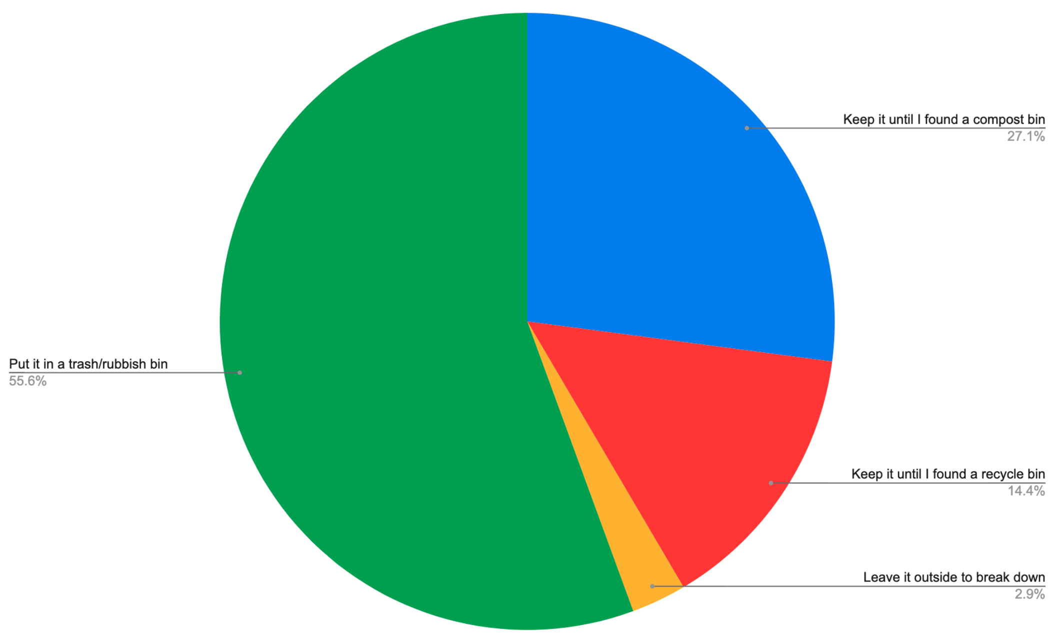

Figure 25. *Breakdown of how all survey respondents typically dispose of a compostable food wrapper.*

6. Discussion & Recommendations

6.1 LCA Environmental Impact Considerations

Based on our life cycle assessment results, algal flexible film's production baseline scenario has significantly higher environmental impacts than LDPE. To be comparable to or better than LDPE, which is achieved in Scenario 6, several adjustments to the production process must be made. Scenario 6 performs equivalently or better than LDPE across impact categories as shown in Figure 33 below. Due to extrapolation uncertainties of measurable midpoint environmental impacts to endpoint outcomes, LCA practitioners have established thresholds for determining the significance of the difference between the product systems being compared (Jolliet et al., 2015). For example, the GWP for the two materials should differ by greater than 10% to be considered significantly different (Jolliet et al., 2015). Scenario 6 GWP is 30% and LDPE is 21% when excluding or including biogenic carbon, respectively. Therefore, Scenario 6 performs significantly better than LDPE for this category. Similarly, Scenario 6 significantly outperforms LDPE for eutrophication and acidification potentials because its impacts in these categories are lower than those of LDPE by more than 30% (Jolliet et al., 2015). Toxicity measures have significant uncertainty, so differences must be an order of magnitude apart to be considered significant (Jolliet et al., 2015). Though our LCA finds that LDPE has lower human toxicity scores than Scenario 6, the performance of the materials cannot be considered significantly different because the toxicity results do not span an order of magnitude but rather are 4.52 and 1.86 times higher for cancer and non-cancer potential, respectively (Jolliet et al., 2015). The potential for smog formation must differ by 30% to be significant (Jolliet et al., 2015). This indicator is only 1.07 times higher for the algal flexible film than for LDPE, so the two cannot be considered significantly different for this category.

Table 33. *Comparison of LDPE performance to that of Scenario 6 and significance of differences in impact category values from Jolliet et al., 2015.*

Impact category	**LDPE**	**Scenario 6 (best case)**	**Required difference for significance**	**Material with significantly lower impact**
AP [kg SO_2 eq.]	1.00	0.54	30%	Scenario 6
Ecotoxicity [CTUe]	1.00	-13.56	1000%	Scenario 6
GWP, excl. biogenic carbon [kg CO_2 eq.]	1.00	0.30	10%	Scenario 6
GWP, incl. biogenic carbon [kg CO_2 eq.]	1.00	0.21	10%	Scenario 6
Human toxicity, cancer [CTUh]	1.00	4.52	1000%	Not significant

Human toxicity, non-canc. [CTUh]	1.00	1.86	1000%	Not significant
Smog [kg O_3 eq.]	1.00	1.07	30%	Not significant
EP [kg N eq.]	1.00	-687.68	30%	Scenario 6

The most significant improvement from a single unit-process change was seen in Scenario 3 when the seaweed was dried in the sun instead of using electricity. In this scenario, there were large reductions in most environmental impact categories. Even changing the drying source to natural gas (Scenario 4) from electricity lowered environmental impacts. Despite the impact reductions from natural gas drying, Scenario 4 had a noticeably higher impact than LDPE across all categories except for eutrophication potential.

However, changes to drying alone do not yet make algal flexible film comparable to LDPE. Moving from the cultivation of seaweed to wild harvest, as seen in Scenario 2, also lowered environmental impacts. For ecotoxicity and human toxicity, switching to wild harvesting brings the impacts to less than an order of magnitude apart, not constituting a significant difference between the values (Jolliet et al., 2015). Additionally, if useful co-products are created during the phycocolloid extraction phase, environmental impacts are also lowered across all impact categories, especially for ecotoxicity. All these changes combined, as seen in Scenario 6, result in a product that is comparable to, or even better than, LDPE.

Despite our best-case scenario being comparable to or better than LDPE for all impact categories including GWP, there are uncertainties when factoring in the feasibility and scalability of this particular production scenario. Additionally, it is yet to be seen whether the impacts found in our results for one polybag scale linearly for mass production volumes. Two important questions that remain are: 1) if sun drying seaweed can be scaled, and 2) if impact reductions due to its feasibility at a small scale would remain if algal flexible film packaging became the industry standard. Moreover, time scales for growing seaweed, as well as approval for worldwide seaweed farms, raise concerns if seaweed alone can meet the global demand. If the present 6.2% growth rate for seaweed cultivation continued through 2050, approximately 252 million tonnes of wet seaweed biomass could be cultivated annually. This would not meet the demand for seaweed as a food source and as an ingredient for consumer products (Duarte et al., 2022). On the other hand, if the scaling rate were doubled to 12%, nearly 2,000 million tonnes of wet seaweed biomass could be produced by 2050, which may reach levels sufficient to meet growing demand (Duarte et al., 2022).

Although we modeled wild harvest in our best-case scenario, it is highly unlikely that this would supply enough seaweed to match LDPE's current production scale while also meeting the demand for other consumer products and seaweed-based food items. Wild-harvested seaweeds yield roughly 800,000 tonnes of wet mass per year (Monagail et al., 2017). Approximately, 19 million tonnes of LDPE is produced annually (Dietrich et al., 2018). Therefore, it would not be feasible for wild-harvested seaweed stocks to be productive enough to completely replace LDPE, making it necessary to optimize seaweed cultivation infrastructure and methods to improve environmental performance while increasing yields. It is unclear whether seaweed cultivation expansion and yield increases will continue, but they are achievable with continued technological development (Duarte et al., 2022). Currently, a majority of impacts from seaweed cultivation stem from the production and use of marine-grade stainless steel and polypropylene longline. Both of these are used for their durability, but researchers should explore alternative structures that reduce environmental impact without decreasing product yield.

It is unclear how scaled production would impact end-of-life impacts, as this research is limited by data availability for algal flexible film disposal outcomes and emissions. Further limitations to this study arise from the novelty of the product and the lack of high-quality primary data. As noted earlier, we used secondary sources to address data gaps and scaled the relevant inventory models to match our product system, assuming linear scaling.

6.2 Non-LCA Environmental Impact Considerations

Using GaBi, we can model and quantify the emissions to air and water from different end-of-life scenarios, but our life cycle assessment results are limited in their ability to analyze some elements of algal flexible film production. While we were able to quantify nutrient uptake and carbon sequestration in biomass during seaweed cultivation, we could not account for the potential for seaweed-derived products to leave no waste footprint and provide ecosystem services from seaweed cultivation.

Compostable materials leave no waste, and they decompose into fertile soil (Farhidi et al., 2022). This feature is increasingly significant and desirable in packaging as plastic pollution increases in severity. It also increases as our understanding of plastic waste as a significant source of microplastics, which transport harmful volatile organic compounds and various co-contaminants to surrounding environments by air and leachate, grows (Wojnowska-Baryła et al., 2022).

An additional benefit of composting algal flexible films is that they may provide important nutrients that plants uptake. In conventional agriculture, the heavy use of inorganic fertilizers depletes soils of essential nutrients (U.S. EPA, 2019). Therefore, the transition to algal flexible film packaging may be an important step in finding alternative ways to fertilize agricultural land without leading to excessive agricultural runoff and its consequential eutrophication.

Seaweed cultivation itself may offer extensive ecosystem services. New research shows that seaweed cultivation may sequester carbon in soils on a longer timescale than it is sequestered in biomass (Duarte et al., 2023). Additionally, seaweeds supply habitats for diverse species and can provide coastal protection (Gentry et al., 2019; Umanzor and Stephens, 2023).

6.2.1 *Disposal Pathways Considerations*

Our goal of the survey was to determine PANGAIA consumers' and non-consumers' access to various waste services and their likelihood of engaging with that service. Although we are not able to draw statistically significant conclusions from this research due to our small survey respondent pool, we can gain a better understanding of disposal trends.

From our survey, we found that a high percentage of survey respondents have access to recycling and composting services at home. When answering the question, "To the best of your knowledge, which of the following waste management services are provided by your municipality or are available to your household?" 85% of respondents stated that they have access to recycling services while 48% of respondents stated they have access to industrial composting and/or backyard/garden composting. The higher percentage of access to recycling services demonstrates that recyclable materials may be a more viable solution for PANGAIA's packaging choice.

Although access to both of these services is high, the survey's findings around disposal behavior may be a better indicator of the likelihood of engaging with a disposal pathway. When comparing the questions, "After you opened your PANGAIA product, what did you do with the box?" and, "After you opened your PANGAIA product, what did you do with the film packaging?" it became apparent that survey respondents were more likely to engage with recycling over composting. Sixty-five percent of PANGAIA consumer survey respondents stated they recycled the box, as seen in Figure 30, while only 28% of PANGAIA consumer survey respondents composted their flexible film packaging. These percentages further highlight that recyclable materials may be an appropriate packaging solution since recycling behavior is already widespread. Therefore, if a compostable packaging solution was pursued, a significant amount of consumer awareness, education, and participation would be necessary to achieve composting rates that are similar to today's recycling rates.

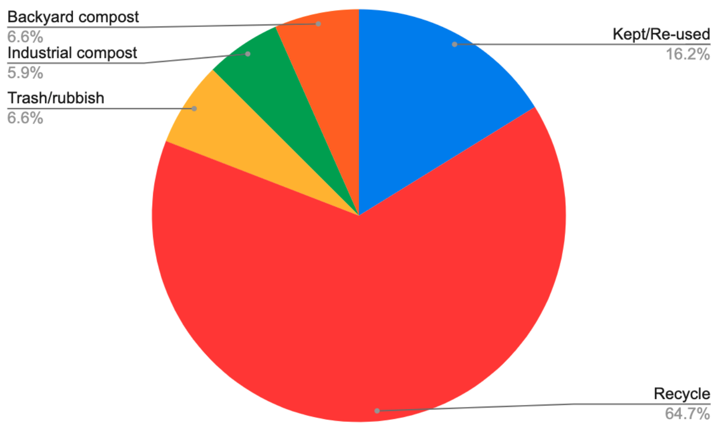

Figure 26. *How PANGAIA consumers disposed of the cardboard box after opening their PANGAIA product.*

We found a trend between consumers and non-consumers in terms of how their household handles food waste. When asked the question, "How does your household handle food waste?" 58% of PANGAIA consumers reported that they use some form of composting (industrial, backyard/garden, at-home device, or drop-off location) in comparison to 42% of non-consumers. A possible reason for this difference is that, given the nature of PANGAIA's mission, PANGAIA consumers may be more likely to be environmentally conscious. This data indicates that, since PANGAIA consumers are more likely to compost their food waste, they will likely be more willing to dispose of an algal flexible film via compost. Nonetheless, the PANGAIA consumer survey respondent pool is small; therefore, the company should attempt to survey a larger portion of its consumer base to better understand the likelihood of engaging with various waste disposal methods and generalize the findings.

In the survey, we asked, "How would you typically dispose of a compostable food wrapper?" We found that over half of respondents normally would put it in a trash/rubbish bin, and nearly a quarter of respondents would keep it until they found a compost bin. The quarter of respondents who stated they would keep the wrapper until they found a compost bin signifies a considerable portion of consumers prioritize composting; therefore, an even larger portion of consumers are likely open to the idea of composting. The data indicate that compostable algal flexible film can become a viable packaging solution in the future, but at the present moment, too few people prioritize composting in order for the benefits to be fully achieved.

Most LDPE and food waste – our proxy for algal flexible film – ends up in landfill (U.S. EPA, 2020). For LDPE, landfilling as a percent of generation is 88%, and for food, landfilling as a percent of generation is 77.75% (Milbrandt et al., 2022; U.S. EPA, 2020). LDPE's waste footprint would be reduced if recycling infrastructure were improved and more individuals recycled. At present, LDPE recycling is difficult because of its low density, low melting point, and the presence of additives that affect the properties of the recycled material and likely contaminate the waste stream (Guo et al., 2022). There have been technological improvements in mechanical plastic sorting via material recognition software and sensors. With technological advancements and a growing commitment to sustainability, LDPE recycling will likely continue to improve. However, this solution might not be feasible due to the high costs required to develop and implement recycling infrastructure at scale (Hopewell et al., 2009; Kosior and Mitchell, 2020). Further, recycling plastics without reducing the amount of primary plastics produced does not decrease waste, it just delays the creation of it (Geyer, 2020).

Unfortunately, when compostable materials are landfilled, they often undergo anaerobic digestion. During this process, bacteria break down organic matter in the absence of oxygen, resulting in methane and CO_2 production (U.S. EPA, 2019). Methane is a more potent greenhouse gas than the CO_2 released during aerobic decomposition in a compost environment (Farhidi et al., 2022). However, because we do not have data on how algal flexible films degrade in an anaerobic environment, we cannot say with certainty how they would behave in a landfill. By increasing the ratio of composted waste in the U.S. from 10% to 18%, carbon emissions could be reduced by 30 million tons per year (Farhidi et al., 2022). Replacing petroplastics with algal flexible film would likely positively shift the proportion of compostable materials entering our waste streams, but a major systemic change – in terms of consumer awareness, education, and participation – would still be needed to achieve the emissions savings potential offered by large-scale composting (Farhidi et al., 2022).

In the U.S., only 4.1% of food is composted while 68% of paper and paperboard are recycled (U.S. EPA 2020; U.S. EPA, 2017). These highly different disposal rates suggest that in the near-term, recyclable packaging materials may be easier for individuals to properly manage based on recycling availability and current consumer behavior. To achieve the full benefits of a compostable packaging solution, the availability of composting services would need to increase substantially. Widespread consumer education about what is compostable and what the benefits of composting would also be necessary to fully realize composting benefits. Composting is a crucial waste stream to achieve emission targets; therefore, a substantial increase in its availability as a service and consumer engagement with the waste stream is inevitable. As this cultural shift takes place, algal flexible films will likely play an important role as an alternative to LDPE film packaging to address the global plastic pollution crisis.

Overall, the impacts from the end-of-life treatment of either material had small impacts relative to the cradle-to-gate impacts. As a result, the benefits of improving composting or recycling rates and, correspondingly, decreasing landfilling, are not as significant as the benefit of optimizing material production processes.

6.3 Recommendations and Future Work

Algal flexible film production can theoretically be optimized to be competitive with LDPE. Future research should focus on optimizing and scaling production to achieve equivalent or lower impacts than LDPE in practice. If production optimization were achieved, the added benefits offered by algal flexible film leaving no waste and contributing nutrients back to the environment would make it an effective alternative to LDPE.

6.3.1 Seaweed Drying

Future research should focus on testing different approaches to optimize seaweed drying. The seaweed drying step contributes a significant portion of the GWP across all models when using large amounts of electricity. When electricity is substituted for natural gas, GWP is lower. Sun drying is the environmentally preferred drying method; however, if production is scaled up, this may not continue to be a viable method. We did not consider powering electric drying with renewable energy sources in this paper, so future research should also investigate the viability of, and impacts from, that method.

There should also be a consideration for a drying approach that incorporates passive and active drying. After seaweed is removed from the water, it begins air drying. Based on a study that discovered that as time passes while *Gundelia tournefortii* is dried with microwave-hot air, the moisture ratio reduction rate decreases (see Figure 27), we hypothesize that the highest drying rate takes place shortly after the seaweed is removed from water (Karimi et al., 2020). This means that an energy-independent drying process is likely efficient enough until a certain point, depending on the ambient temperature and humidity levels. Researchers can focus on understanding how these factors impact the drying rate to produce a best-practice recommendation for sun drying. This information can be used to help seaweed companies incorporate a certain level of energy-independent drying into their business operations to decrease seaweed drying's energy impact.

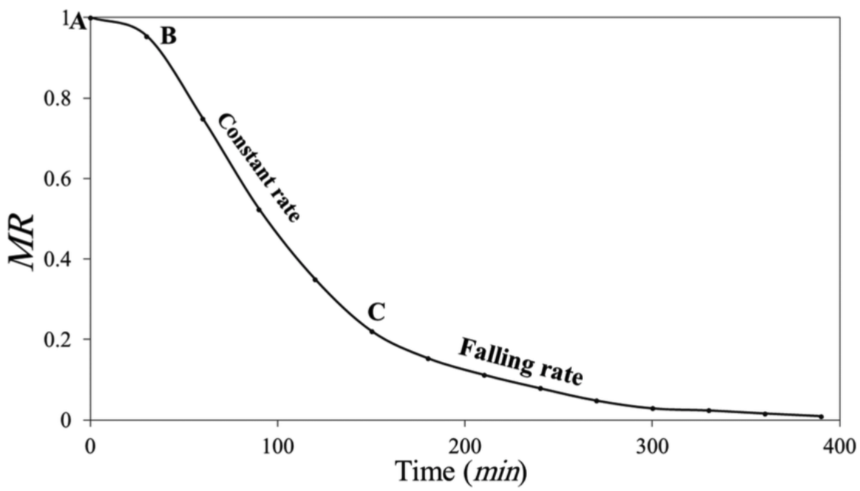

Figure 27. Drying curve of hot air drying at a temperature of 45 °C (Karimi et al., 2020)

6.3.2 Seaweed Species

Expanded seaweed stocks for consumer products are necessary to make algal flexible film viable at scale. As stated previously, wild-harvested seaweed could not be used if algal flexible film replaces LDPE flexible film one-for-one, but at current production scales, the transition could be possible. There are over 1,200 seaweed species on Earth, so additional research should explore which seaweed species can be cultivated with high yields to make the impact of cultivation infrastructure per mass of material lower (Guiry and Guiry, 2023).

6.3.3 Phycocolloid Extraction

Further optimization and efficiency improvements are needed as material production scales. For instance, phycocolloid extraction produces a considerable amount of waste, with a 34% approximate alginate yield from dry seaweed biomass (Nilsson et al., 2022). This process could be optimized to make phycocolloid extraction more efficient and generate useful co-products. The co-products from phycocolloid extraction that are modeled within this LCA are film produced from cellulosic residues, electricity from biogas, and fertilizer (NH_3) from a digestate. Nonetheless, extracting co-products from this process is not yet standard, and few studies have assessed seaweed-based refinery's environmental impacts for both phycocolloid and co-products (Nilsson et al., 2022). Additional methods for generating useful co-products should be explored to further reduce process impacts (Beckstrom et al., 2020). Subsequent research should focus on determining how the waste material that is generated during algal processing can be utilized to strengthen the algae industry's circularity by using this waste as a feedstock to substitute less environmentally-preferred ingredients in consumer products. These improvements could allow the algal flexible film's environmental performance to be comparable to that of LDPE while offering benefits that are not currently applicable to LCAs. Examples include seaweed's ecosystem services, its circularity potential, and the public's positive perception of bio-based products (Dilkes-Hoffman et al., 2019).

6.3.4 End-of-Life

To better understand algal flexible film's end-of-life impacts, researchers can pursue projects that aim to quantify the nutrients that result from flexible film decomposition. This data can be used to provide more context into why algal flexible films may be environmentally beneficial to soil health if added as a fertilizer. Another area of future research around composting algal flexible film is the material's GWP due to its re-release of CO_2 during decomposition. Our LCA model has a relatively small amount of the algal flexible film going into compost; therefore, the end-of-life pathway may be an inaccurate representation of its greenhouse gas emission magnitude. Further research could provide a better understanding of the anticipated GWP due to organic decomposition as the seaweed flexible film industry scales compared to the GWP that would be avoided through a reduction in the plastics industry. Additionally, new research is emerging that demonstrates seaweed's potential to sequester carbon in soils over a longer time period than it sequesters carbon in its biomass. This means that there may be additional GWP avoidance that we did not model as we accounted for temporary biomass sequestration only (Duarte et al., 2023).

Lastly, there is limited research on how algal flexible film behaves in the landfill. This LCA modeled the flexible film as plastic waste with some minor adjustments to help improve the accuracy of the model. Therefore, our results may not be fully representative of the greenhouse gasses that the algal flexible film emits during anaerobic decomposition. Since landfilling is more commonly used for organic waste disposal, further insight into how algal flexible films degrade in this setting is crucial.

7. References

About PANGAIA. (n.d.). PANGAIA. https://pangaia.com/pages/about-us.

Bare, J. C., Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI), Version 2.1 - User's Manual; EPA/600/R-12/554 2012.

Beckstrom, B. D., Wilson, M. H., Crocker, M., & Quinn, J. C. (2020). Bioplastic feedstock production from microalgae with fuel co-products: A techno-economic and life cycle impact assessment. *Algal Research*, *46*, 101769. https://doi.org/10.1016/j.algal.2019.101769.

Birol, D. F. (2017). *Tracking Clean Energy Progress 2017*. https://iea.blob.core.windows.net/assets/580c0f94-0db8-4dc8-9947-66720737cb3a/TrackingCleanEnergyProgress2017.pdf.

Chia, W. Y., Ying Tang, D. Y., Khoo, K. S., Kay Lup, A. N., & Chew, K. W. (2020). Nature's fight against plastic pollution: Algae for plastic biodegradation and bioplastics production. *Environmental Science and Ecotechnology*, *4*, 100065. https://doi.org/10.1016/j.ese.2020.100065.

Collins, N., Kumar Mediboyina, M., Cerca, M., Vance, C., & Murphy, F. (2022). Economic and environmental sustainability analysis of seaweed farming: Monetizing carbon offsets of a brown algae cultivation system in Ireland. *Bioresource Technology*, *346*, 126637. https://doi.org/10.1016/j.biortech.2021.126637.

Dang, B.-T., Bui, X.-T., Tran, D. P. H., Hao Ngo, H., Nghiem, L. D., Hoang, T.-K.-D., Nguyen, P.-T., Nguyen, H. H., Vo, T.-K.-Q., Lin, C., Yi Andrew Lin, K., & Varjani, S. (2022). Current application of algae derivatives for bioplastic production: A review. *Bioresource Technology*, *347*, 126698. https://doi.org/10.1016/j.biortech.2022.126698.

Devadas, V. V., Khoo, K. S., Chia, W. Y., Chew, K. W., Munawaroh, H. S. H., Lam, M.-K., Lim, J.-W., Ho, Y.-C., Lee, K. T., & Show, P. L. (2021). Algae biopolymer towards sustainable circular economy. *Bioresource Technology*, *325*, 124702. https://doi.org/10.1016/j.biortech.2021.124702.

Di Bartolo, A., Infurna, G., & Dintcheva, N. T. (2021). A Review of Bioplastics and Their Adoption in the Circular Economy. *Polymers*, *13*(8), Article 8. https://doi.org/10.3390/polym13081229.

Dilkes-Hoffman, L., Ashworth, P., Laycock, B., Pratt, S., & Lant, P. (2019). Public attitudes towards bioplastics – knowledge, perception and end-of-life management. *Resources, Conservation and Recycling*, *151*, 104479. https://doi.org/10.1016/j.resconrec.2019.104479.

Duarte, C. M., Bruhn, A., & Krause-Jensen, D. (2022). A seaweed aquaculture imperative to meet global sustainability targets. Nature Sustainability, 5(3), Article 3. https://doi.org/10.1038/s41893-021-00773-9.

Duarte, C. M., Delgado-Huertas, A., Marti, E., Gasser, B., Martin, I. S., Cousteau, A., Neumayer, F., Reilly-Cayten, M., Boyce, J., Kuwae, T., Hori, M., Miyajima, T., Price, N., Arnold, S., Martinez-Ricart, A., Davis, S., Surugau, N., Abdul, A.-J., Wu, J., … Masque, P. (2023). *Carbon Sequestration in Soils below Seaweed Farms* (p. 2023.01.02.522332). bioRxiv. https://doi.org/10.1101/2023.01.02.522332.

Duarte, C. M., Jiaping Wu, Xi Xiao, Annette Bruhn, & Dorte Krause-Jensen. (2017). Can Seaweed Farming Play a Role in Climate Change Mitigation and Adaptation? *Frontiers in Marine Science*, *4*(2017). https://doi.org/10.3389/fmars.2017.00100.

Eggertsen, M., & Halling, C. (2021). Knowledge gaps and management recommendations for future paths of sustainable seaweed farming in the Western Indian Ocean. *Ambio*, *50*(1), 60–73. https://doi.org/10.1007/s13280-020-01319-7.

European Commission. (2007). *Reference Document on Best Available Techniques in the Production of Polymers*. https://eippcb.jrc.ec.europa.eu/sites/default/files/2019-11/pol_bref_0807.pdf.

Farhidi, F., Madani, K., & Crichton, R. (2022). How the US Economy and Environment can Both Benefit From Composting Management. *Environmental Health Insights*, *16*, 11786302221128454. https://doi.org/10.1177/11786302221128454.

Feber, D., Granskog, A., Lingqvist, O., & Nordigarden, D. (n.d.). *How US consumers view sustainability in packaging | McKinsey*. Retrieved March 24, 2023, from https://www.mckinsey.com/industries/paper-forest-products-and-packaging/our-insights/sustainability-in-packaging-inside-the-minds-of-us-consumers.

Fei, X. (2004). Solving the coastal eutrophication problem by large scale seaweed cultivation. *Asian Pacific Phycology in the 21st Century: Prospects and Challenges, Springer*, *173*, 145–151.

Gentry, R., Heidi K. Alleway, Melanie J. Bishop, Chris L. Gillies, Tiffany Waters, & Robert Jones. (2019). Exploring the potential for marine aquaculture to contribute to ecosystem services. *Reviews in Aquaculture*, *12*(2). https://doi.org/10.1111/raq.12328.

Geyer, R., Jambeck J., Law K. (2017). *Production, use, and fate of all plastics ever made | Science Advances*. (n.d.). Retrieved March 22, 2023, from https://www.science.org/doi/10.1126/sciadv.1700782.

Geyer, R. (2020). A Brief History of Plastics. In M. Streit-Bianchi, M. Cimadevila, & W. Trettnak (Eds.), *Mare Plasticum—The Plastic Sea: Combatting Plastic Pollution Through Science and Art* (pp. 31–47). Springer International Publishing. https://doi.org/10.1007/978-3-030-38945-1_2

Guiry, M.D. & Guiry, G.M. (2023). AlgaeBase. World-wide electronic publication, National University of Ireland, Galway. https://www.algaebase.org.

Guo, J., Kim, Y., Chong, Z. K., Alassali, A., Chacon, J. P., Gottschalk, D., Kitzberger, M., & Kuchta, K. (2022). Quality Changes of Low-Density Polyethylene (LDPE) Recyclates from the Pretreatment Process with a Cationic Surfactant and a Nonionic Surfactant as Cleaning Agents Upstream of Extrusion. *Processes*, *10*(11), Article 11. https://doi.org/10.3390/pr10112174.

Hall, M. (2014). *97% of UK households don't compost. Britain forgets the art of composting*. Business Waste. https://www.businesswaste.co.uk/97-of-uk-households-dont-compost-britain-forgets-the-art-of-composting/.

Holding, Ashley, Adam Gendell, Erin Hiatt, Scott Nelson. (2019). Polybags in the fashion industry: evaluating the options. https://fashionforgood.com/wp-content/uploads/2019/12/FashionforGood_Polybags_in_the_Fashion_Industry_Whitepaper-1.pdf.

Hopewell, J., Dvorak, R., & Kosior, E. (2009). Plastics recycling: Challenges and opportunities. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1526), 2115–2126. https://doi.org/10.1098/rstb.2008.0311.

Japan International Cooperation Agency. (n.d.). *Chapter 4. Process Description*. Japan International Cooperation Agency. Retrieved December 8, 2022, from https://openjicareport.jica.go.jp/pdf/10467090_02.pdf.

Jestratijevic, I., & Vrabič-Brodnjak, U. (2022). Sustainable and Innovative Packaging Solutions in the Fashion Industry: Global Report. *Sustainability*, *14*(20), Article 20. https://doi.org/10.3390/su142013476.

Jolliet, O., Saade-Sbeih, M., Shaked, S., Jolliet, A., & Crettaz, P. (2015). Environmental Life Cycle Assessment (1st ed.). CRC Press. https://doi.org/10.1201/b19138.

Karimi, Safoora, et al. (2020). Microwave Pretreatment Followed by Associated Microwave-Hot Air Drying of Gundelia Tournefortii L.: Drying Kinetics, Energy Consumption and Quality Characteristics - Heat and Mass Transfer. *SpringerLink*, https://link.springer.com/article/10.1007/s00231-020-02948-0.

Kätelhön, A., Meys, R., Deutz, S., Suh, S., & Bardow, A. (2019). Climate change mitigation potential of carbon capture and utilization in the chemical industry. *Proceedings of the National Academy of Sciences*, *116*(23), 11187–11194. https://doi.org/10.1073/pnas.1821029116.

Kosior, E., & Mitchell, J. (2020). Chapter 6—Current industry position on plastic production and recycling. In T. M. Letcher (Ed.), *Plastic Waste and Recycling* (pp. 133–162). Academic Press. https://doi.org/10.1016/B978-0-12-817880-5.00006-2.

Krause-Jensen, D., Paul Lavery, Oscar Serrano, Núria Marbà, Pere Masque, & Carlos M. Duarte. (2018). Sequestration of macroalgal carbon: The elephant in the Blue Carbon room. *The Royal Society Publishing: Biology Letters*. https://doi.org/10.1098/rsbl.2018.0236.

Krumpal, I. (2013). Determinants of social desirability bias in sensitive surveys: A literature review. *Quality & Quantity*, *47*(4), 2025–2047. https://doi.org/10.1007/s11135-011-9640-9.

Kyaw, B. M., Champakalakshmi, R., Sakharkar, M. K., Lim, C. S., & Sakharkar, K. R. (2012). Biodegradation of Low Density Polythene (LDPE) by Pseudomonas Species. *Indian Journal of Microbiology*, *52*(3), 411–419. https://doi.org/10.1007/s12088-012-0250-6.

Light, Larry. "2021: The Year Of The Package." Forbes. Accessed March 22, 2023. https://www.forbes.com/sites/larrylight/2021/01/04/2021-the-year-of-the-package/.

Lomartire, S., Marques, J. C., & Gonçalves, A. M. M. (2022). An Overview of the Alternative Use of Seaweeds to Produce Safe and Sustainable Bio-Packaging. *Applied Sciences*, *12*(6), Article 6. https://doi.org/10.3390/app12063123.

Mac Monagail, M., Cornish, L., Morrison, L., Araújo, R., & Critchley, A. T. (2017). Sustainable harvesting of wild seaweed resources. *European Journal of Phycology*, *52*(4), 371–390. https://doi.org/10.1080/09670262.2017.1365273.

Malone, T. C., & Newton, A. (2020). The Globalization of Cultural Eutrophication in the Coastal Ocean: Causes and Consequences. *Frontiers in Marine Science*, *7*. https://doi.org/10.3389/fmars.2020.00670.

Marinho, G. S., Holdt, S. L., Birkeland, M. J., & Angelidaki, I. (2015). Commercial cultivation and bioremediation potential of sugar kelp, Saccharina latissima, in Danish waters. *Journal of Applied Phycology*, *27*(5), 1963–1973. https://doi.org/10.1007/s10811-014-0519-8.

Mashoreng, S., Y A La Nafie, & R Isyrini. (2019). Cultivated seaweed carbon sequestration capacity. *IOP Conference Series: Earth and Environmental Science*, *371*(012017). https://iopscience.iop.org/article/10.1088/1755-1315/370/1/012017/pdf.

Michal, B. (2022). *How much are we composting in the United States?* Better Earth. https://becompostable.com/how-much-are-we-composting-in-the-united-states/.

Milbrandt, A., Coney, K., Badgett, A., & Beckham, G. T. (2022). Quantification and evaluation of plastic waste in the United States. *Resources, Conservation and Recycling*, *183*, 106363. https://doi.org/10.1016/j.resconrec.2022.106363.

Murie K., & Bourdeau P. (2020). Fragmented kelp forest canopies retain their ability to alter local seawater chemistry. *Scientific Reports*, *10*(11939). https://www.nature.com/articles/s41598-020-688412#:~:text=Kelp%20forests%20support%20some%20of,and%20oxygen%20in%20their%20vicinity.

Nilsson, A. E., Bergman, K., Gomez Barrio, L. P., Cabral, E. M., & Tiwari, B. K. (2022). Life cycle assessment of a seaweed-based biorefinery concept for production of food, materials, and energy. *Algal Research*, *65*, 102725. https://doi.org/10.1016/j.algal.2022.102725.

Pangestuti, R., & Kim, S.-K. (2015). An Overview of Phycocolloids: The Principal Commercial Seaweed Extracts. In *Marine Algae Extracts* (pp. 319–330). John Wiley & Sons, Ltd. https://doi.org/10.1002/9783527679577.ch19.

Peng, Yiming, Peipei Wu, Amina T. Schartup, and Yanxu Zhang. "Plastic Waste Release Caused by COVID-19 and Its Fate in the Global Ocean." Proceedings of the National Academy of Sciences 118, no. 47 (November 23, 2021): e2111530118. https://doi.org/10.1073/pnas.2111530118.

Pham, Nga Thi-Hong. (2021). Characterization of Low-Density Polyethylene and LDPE-Based/Ethylene-Vinyl Acetate with Medium Content of Vinyl Acetate. *Polymers (Basel)*, *14*(2352). https://doi.org/10.3390/polym13142352.

Piccinno, F., Hischier, R., Seeger, S., & Som, C. (2015). Life Cycle Assessment of a New Technology To Extract, Functionalize and Orient Cellulose Nanofibers from Food Waste. *ACS Sustainable Chemistry & Engineering*, *3*(6), 1047–1055. https://doi.org/10.1021/acssuschemeng.5b00209.

Plasticfilmrecycling.org, *Find a Drop Off Location - Plastic Film Recycling*. https://www.plasticfilmrecycling.org/recycling-bags-and-wraps/find-drop-off-location/.

Radulovich, R., Neori, A., Valderrama, D., Reddy, C. R. K., Cronin, H., & Forster, J. (2015). Chapter 3—Farming of seaweeds. In B. K. Tiwari & D. J. Troy (Eds.), *Seaweed Sustainability* (pp. 27–59). Academic Press. https://doi.org/10.1016/B978-0-12-418697-2.00003-9.

Roberts-Islam, B. (n.d.). *This Startup Is Reshaping What It Means To Be A Sustainable Fashion Brand, From Materials Through To Products*. Forbes. Retrieved March 24, 2023, from https://www.forbes.com/sites/brookerobertsislam/2019/12/05/this-startup-is-reshaping-what-it-means-to-be-a-sustainable-fashion-brand-from-materials-through-to-products/.

Rodrigues, M. O., Abrantes, N., Gonçalves, F. J. M., Nogueira, H., Marques, J. C., & Gonçalves, A. M. M. (2019). Impacts of plastic products used in daily life on the environment and human health: What is known? *Environmental Toxicology and Pharmacology*, *72*, 103239. https://doi.org/10.1016/j.etap.2019.103239.

Romera-Castillo C., Arturo Lucas, Rebeca Mallenco-Fornies, Marina Briones-Rizo, Eva Calvo, & Carles Pelejero. (2023). Abiotic plastic leaching contributes to ocean acidification. *Science of The Total Environment*, *854*(1). https://doi.org/10.1016/j.scitotenv.2022.158683.

Ronca, S. (2017). Polyethylene. In *Brydson's Plastics Materials: Eighth Edition* (pp. 247–278). https://doi.org/10.1016/B978-0-323-35824-8.00010-4.

Ross, F., Patrick Tarbuck, & Peter Macreadie. (2022). Seaweed afforestation at large-scales exclusively for carbon sequestration: Critical assessment of risks, viability and the state of knowledge. *Frontiers in Marine Science*, *9*(2022). https://doi.org/10.3389/fmars.2022.1015612.

Schiener, P., Black, K. D., Stanley, M. S., & Green, D. H. (2015). The seasonal variation in the chemical composition of the kelp species Laminaria digitata, Laminaria hyperborea, Saccharina latissima and Alaria esculenta. *Journal of Applied Phycology*, *27*(1), 363–373. https://doi.org/10.1007/s10811-014-0327-1.

Shahul Hamid, F., Bhatti, M. S., Anuar, N., Anuar, N., Mohan, P., & Periathamby, A. (2018). Worldwide distribution and abundance of microplastic: How dire is the situation? *Waste Management & Research*, *36*(10), 873–897. https://doi.org/10.1177/0734242X18785730.

Sondak, C.F.A., Ang, P.O., Beardall, J. (2017). *Carbon dioxide mitigation potential of seaweed aquaculture beds (SABs)*. J Appl Phycol 29, 2363–2373 (2017).

Szlachetka O., Joanna Witkowska-Dobrev, Anna Baryła, & Marek Dohoj. (2021). Low-density polyethylene (LDPE) building films – Tensile properties and surface morphology. *Journal of Building Engineering*, *44*(103386). https://doi.org/10.1016/j.jobe.2021.103386.

Thomas, J.-B. E., Sodré Ribeiro, M., Potting, J., Cervin, G., Nylund, G. M., Olsson, J., Albers, E., Undeland, I., Pavia, H., & Gröndahl, F. (2021). A comparative environmental life cycle assessment of hatchery, cultivation, and preservation of the kelp Saccharina latissima. *ICES Journal of Marine Science*, *78*(1), 451–467. https://doi.org/10.1093/icesjms/fsaa112.

Troell, M, P. J. G. Henricksson, A. H. Buschmann, T. Chopin, & S. Quahe. (2022). Farming the Ocean – Seaweeds as a Quick Fix for the Climate? *Reviews in Fisheries Science & Aquaculture*. https://doi.org/ttps://doi.org/10.1080/23308249.2022.2048792.

Umanzor, S., & Stephens, T. (2023). Nitrogen and Carbon Removal Capacity by Farmed Kelp Alaria marginata and Saccharina latissima Varies by Species. *Aquaculture Journal*, *3*(1), Article 1. https://doi.org/10.3390/aquacj3010001.

U.S. Energy Information Administration (EIA). (2021). Retrieved March 20, 2023, from https://www.eia.gov/tools/faqs/faq.php?id=34&t=6.

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

U.S. EPA. (2019). *How Does Anaerobic Digestion Work?* [Overviews and Factsheets]. https://www.epa.gov/agstar/how-does-anaerobic-digestion-work.

U.S. EPA. (2020). *Advancing Sustainable Materials Management: 2018 Fact Sheet*. https://www.epa.gov/sites/default/files/2021-01/documents/2018_ff_fact_sheet_dec_2020_fnl_508.pdf.

U.S. EPA. (2022). *Understanding Global Warming Potentials* [Overviews and Factsheets]. https://www.epa.gov/ghgemissions/understanding-global-warming-potentials.

van Oirschot, R., Thomas, J.-B. E., Gröndahl, F., Fortuin, K. P. J., Brandenburg, W., & Potting, J. (2017). Explorative environmental life cycle assessment for system design of seaweed cultivation and drying. *Algal Research*, *27*, 43–54. https://doi.org/10.1016/j.algal.2017.07.025.

Wojnowska-Baryła, Irena, Katarzyna Bernat, and Magdalena Zaborowska. "Plastic Waste Degradation in Landfill Conditions: The Problem with Microplastics, and Their Direct and Indirect Environmental Effects." *International Journal of Environmental Research and Public Health* 19, no. 20 (October 14, 2022): 13223. https://doi.org/10.3390/ijerph192013223.

Xiao X., Susana Agustí, Yan Yu, Yuzhou Huang, Weizhou Chen, Jing Hu, Chao Li, Ke Li, Fangyi Wei, Yitian Lu, Caicai Xu, Zepan Chen, Shengping Liu, Jiangning Zeng, Jiaping Wu, & Carlos M. Duarte. (2021). Seaweed farms provide refugia from ocean acidification. *Science of The Total Environment*, *776*(145192). https://doi.org/10.1016/j.scitotenv.2021.145192.

Xu S., Zonghe Yu, Yi Zhou, Shidong Yue, Junhua Liang, & Xiaomei Zhang. (2023). The potential for large-scale kelp aquaculture to counteract marine eutrophication by nutrient removal. *Marine Pollution Bulletin*, *187*(2023). https://doi.org/10.1016/j.marpolbul.2022.114513.

Zheng J. & Sangwon Suh. (2019). Strategies to reduce the global carbon footprint of plastics. *Nature Climate Change*, *9*, 374–378. https://doi.org/10.1038/s41558-019-0459-z.

Zhong, X., Zhao, X., Qian, Y., & Zou, Y. (2018). Polyethylene plastic production process. *Insight - Material Science*, *1*, 1. https://doi.org/10.18282/ims.v1i1.104.