The Role of Synthetic and Bio-Based Plastics and in the Transition to a Circular Economy

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

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Background

The materials we use and how we use them shapes the world around us. Our species' ability to engineer and manipulate materials is the often-overlooked fabric of societal development. This is exemplified not only in the products we use, but the layers of packaging that surround them, and becomes most problematic when the lifecycle of materials fail to align with the lifecycle of the product in which they're used. The average use of most packaging is only a few days, yet in the environment many of these materials persist hundreds of years beyond their time in use. The resulting misuse and end of life mismanagement of single-use goods and packaging materials is one of the greatest threats global health in the 21st century.

The 300 billion pounds of single-use plastics produced annually are particularly concerning due to their chemically inert nature and tendency to physically fragment into toxic microplastics (Lindwall, 2009). When ingested by animals and humans, microplastics cause crippling birth defects and cancers. Microplastics' rapid accumulation throughout the food web and infiltration of drinking water systems threatens the survival of nearly every species on earth.

The circular economy has been theorized as the saving grace to restore post-industrial human-inflicted environmental damage and prevent it from worsening. This paper uses the historic failures of the 20th and 21st century recycling industry to caution accepting "sustainable" innovations at face value using the circular economy and multi-level perspective (MLP) as the primary and secondary lenses, respectively.

Scope

The idea of a circular economy is often accredited to Kenneth Boulding in 1966, when he theorized functional "open" and "closed" economies. Each was defined by the perceived nature of input resources and output sinks corresponding to the modern understanding of linear and circular economics (Allwood, 2014). The idea has since become a battle cry for sustainability advocacy organizations as one of the most straightforward ways to preserve resources, but, like many principles of sustainable innovation, has been creatively twisted into a new selling point in the existing petroleum-rich value chain, otherwise known as *greenwashing*. Overcoming these tactics is a matter of interactions between the powerful petroleum regime and emerging sustainable niche.

A MLP analysis is often used to define the interaction between the incumbent petroleum regime and the more sustainable niche within the expansive industrial and government landscape. A Hessian interpretation of the traditional MLP approach can be used to analyze the measures taken by the petroleum regime to preserve the relevance and profitability of their materials, exemplifying the previously unforeseen pushback of the regime against the niche sustainable transition. Hess suggests this regime, consisting of immensely powerful international companies and representative trade organizations, "mobilize against [sustainable transition] policies that are perceived to threaten their short-term profitability and long-term existence" (Hess, 2014). This trend remains true, as environmental data and sector analyses suggest little synchronous progress has been made in improving the circularity of consumer goods and packaging.

When looking at the broader single-use plastics industry, there are two prevailing approaches with respect to pollution management: improving existing recycling infrastructure and transitioning to biodegradable alternatives (CXL, 2021). Each of these approaches can be defined by the "loop" that they complete at the product's end of life – either an artificial technical loop or the organic biological loop –; however, the tale of both recycling and bio-based goods has been manipulated, allowing synthetic plastics to continue clogging the biological loop and threatening the health of our planet and species.

Blunders of Traditional Recycling and Bio-Based Branding

Recycling has been successfully implemented in several common material markets (i.e. paperboard, metals); however, a variety of factors have inhibited successful rollout in the plastics arena since it's industrialization in the mid-20th century. The most blatant example of the petroleum industry encouraging incomplete solutions to management of their waste are traditional physical and early chemical recycling. As early as 1974, an industry insider stated, "There is serious doubt that [recycling plastic] can ever be made viable on an economic basis," suggesting it had already become clear to the petroplastics regime that recycling was not the end-all solution to the mounting issue (Sullivan, 2020).

While recycling methodologies and recovery rates have improved slightly in the last few years, recovery of plastics, in particular single-use items, becomes an immense challenge. Contamination, a lack in organized collection infrastructure, the inefficiency of long-distance waste transportation, material quality loss (aka downcycling), product design/use, and a reliance on immense consumer buy-in are some of the leading factors in this decades-long technological blunder. While things seem alright at face value, only a fraction of that which is collected can be processed properly, and only when a buyer is in the market for recycled content can it be resold to keep it from the landfill/incinerator.

A more recent example of the petroleum industry backing an incompletely sustainable innovation is the popularization of bio-based petrochemicals. Since 1947, companies have used natural/organic raw materials to create chemicals of the same molecular composition as those we create from petroleum (Barrett, 2018). Initially, these products were described as natural (i.e. "derived from natural resources") but as time went on, the line between raw material sourcing and composition became ever more blurred (Nemo, 2018). Since the 2002 announcement of the USDA BioPreferred program, confusion has ensued as synthetic plastics have become widely marketed as "bio-based" (USDA, n.d.). While the name sells a significantly cleaner lifecycle than their traditional petroleum-derived counterparts, neither the beginning nor end of life is much of an improvement (especially when accounting for the low 22% bio-based composition threshold needed to meet the standard). The classification is justified by the use of plant-based raw materials, which are then manipulated into the inert synthetic polymers suffocating the planet. At the scale necessitated by annual human plastic consumption, embodied water usage and chemical runoff potentiates an equivalent threat to global balance; meanwhile, "bio-based" products of this nature are treated and act identical to their petroleum-derived counterparts at the end of life unbeknownst to many consumers.

ASTM D4600 – Compostable/Biodegradable Plastics

To complement recycling efforts (albeit small) contribution to the mounting sustainable transition, significant attention has been given to the development and commercialization of compostable and biodegradable polymers to reduce the footprint of plastic goods. These materials act as near one-to-one replacements for the inert petroleum derived chemicals on the shelf and in the hands of the consumer but are intended to degrade with little to no post-use treatment in waste management facilities and the environment.

Biodegradability is a means of achieving circularity through the assimilation of materials back into the natural biocycle. As in the section title, the technical performance of such materials is defined by several non-governmental regulatory organizations around the world. Each organization possesses one or several sets of standards (i.e. ASTMD4600, ISO 14855, etc.) and protocols that can be followed to demonstrate compliance.

The aforementioned ASTM and ISO standards can be traced back to the early 2000s and have since become respected as industry norms. Not too unlike the BioPreferred Program, the terms "bio-based" and "biodegradable" were re-popularized in Europe in 2007-08 in an action by the European Commission's Lead Market Initiative (LMI) to stimulate consumer interest in a greener, bio-based economy by making a large financial commitment to be invested in the years shortly following. In 2008, the Ad-hoc Advisory Group for Bio-based Products, representing European governments, industry and academic was established to innovate in unity towards goals laid out in the LMI (OECD, 2013). The terms highlighted in these goals, such as “bio-based” and “biodegradable,” were defined, though poorly at that. As with recycling, the petroplastic regime has been able to greenwash/bend these seemingly self-explanatory terms in favor of use of their polymers with chemical and biologic additives that render the (products) visibly degradable upon disposal.

Catalyst-mediated “Biodegradable” Petroplastics

Traditional petroplastic products fragment on the timescale of hundreds of years; however, several entities have developed technologies that allow them to break down in only a matter of months. Without further exploration, these innovations have the potential to wreak havoc on the environment under the noses of regulatory and consumer groups. Materials like PBAT and PCL disappear completely to the naked eye, but do not biodegrade and instead fragment more quickly into microplastics and other constituent molecules, causing less visible macro-pollution but posing a significantly larger threat to global and human health.

Methods of catalyst-driven degradation have been researched since the 70s. The first development, commonly known as oxo-degradation (then creatively rebranded as oxo-“biodegradable”), is a chemical additive that utilizes the reactivity of oxygen species with heavy metals under UV and shearing forces to break bonds inserted into the polymers chain. Early on, the technology was investigated by the petroplastic regime, but quickly died out in most applications due to an apparent lack of need for the degradative property (HSAC, 2019). As biodegradability grew more popular in the early 2000s, the petroplastic regime sought to take advantage of the loosely defined standard degradation metrics (formed on the basis of CO_2 production during degradation). Early pushes for these material treatments imagined a world where animals would no longer be choked by plastic products (i.e. straws, plastic rings, etc.) (BSP, n.d.); however, catalyst-driven degradation has been revealed to pose an even greater threat to the preservation of the biosphere. As oxo-degradable bonds undergo catalysis, polystyrene, polyethylene and polypropylene alike break down into a variety of constituent molecular structures, namely heavy metals, ketones, alcohols, acids and hydrocarbon waxes. Except for heavy metals, which toxify waterways and soil, several of these molecules are photo-, mechanically- and bio-degradable under *ideal* circumstances. In addition to the sparsity of "ideal" conditions, these methods fail to account for the more rapid release of plasticizers – toxic additives use to alter material properties that are unbound to the polymer chain and leach over time anyway – alongside other degradation byproducts (EC, 2016).

Since the early 2000s push, several catalyst-mediated degradable plastics have been successfully certified under ASTM D4600, ISO 14855, etc, adding false validity to the existence of these materials in consumer markets (Fine, m.d.). More recent innovations have introduced new catalysts, such as active biologics (enzymes) embedded in the material that are activated by certain environmental conditions to degrade plastics similarly to oxo-derivatives. While adoption of these more novel additives can be chalked up to be an improvement based on the current standards, the long-term effect of their use is yet understood. Since bio-based (molecules have a greener beginning and end of life than petroleum-based materials, these adjacent technological innovations can be considered an unnecessary and potentially dangerous intermediate step in the ongoing sustainable transition.

Pushback from the Bio-focused Niche

Despite the efforts of the petroleum regime to tighten their grasp on the single-use plastics industry, fully bio-based compostable and biodegradable products have gained considerable traction in the last 2-3 years. The term bio-based tolerates two definitions: being composed of a biological-based substance and being manufactured from a bio-based raw material; meanwhile, the terms compostable and biodegradable are closely related and imply material breakdown with and without industrial treatment, respectively.

Until mass industrialization of petroleum refining introduced by World War II, the majority of materials were near-entirely plant based (i.e. hemp, cotton, etc.), though plastic was less widely-used altogether. While polyhydroxybutyrate (PHB) and poly lactic acid (PLA) were discovered in the 1920s, technological limitations did not allow large-scale biomanufacturing until the 60s-70s (Alamgeer, 2019; PLA, 2017). While the idea of "biodegradable" reemerged in the 80s, it was not until the mid/late-90s that the first large commercial measures were taken to commercialize biopolymers like PLA and PHA. These companies, namely NatureWorks and Danimer, are now market leaders and have helped to popularize these materials in spite of the protective measures taken by the petroplastic regime.

As the petroplastic industry has fought to preserve its market dominance, the emerging bio-focused industry and its advocates have fought to prevent these creative marketing tactics from further damaging the health of our planet. The most well-known statements have been made by the Ellen MacArthur Foundation and the European Union. In 2017, the global landscape's (diplomatic and sustainability-promoting organizations) support of the New Plastics Economy initiative published by the Ellen MacArthur Foundation quickly led to a widespread recognition of the flaws of oxo-degradable additives and other petroleum-based plastics (EUBIO, n.d.); however, little policy or standard practice has yet been established to reduce/restrict their use. To compensate, individuals and organizations have taken measures to begin reporting malicious greenwashing intentions (i.e. a "landfill degradable" plastic – an unbased claim) and advocating for more scientifically-rigorous standards/certifications (Fine, m.d.).

Conclusion

Synthetic polymers were engineered to imitate and improve up their bio-based counterparts during use, but key aspects of their lifecycle were overlooked. As the convenience became an ever more appealing selling point, single-use plastics quickly solidified their place around the world.

Over 50 years in the making, recycling practices continue to inappropriately justify the use of unsustainable materials in single-use products and recover less than 9% of all plastics produced annually (Parker, 2017). The misguided faith in recycling and bio-based labelling has allowed consumers to dismiss concern for the longevity of the environment and their own health caused by the unsustainable materials cloaked in a phantom of sustainability. In spite of these historical missteps, catalyst-degradable plastics and the like have successfully penetrated consumer markets under the guise of a new circular innovation. Worse, the confusion instigate by the market's acceptance of these materials has detracted from the advancement of truly sustainable technologies.

In a 2018 MLP analysis of the circular economy, the UN stated, "Specifically, no concrete policy action has yet been taken to promote a rapid transition towards a circular economy paradigm." The document proceeds to encourage consumer participation in circular practices but strictly defines few measures for industry to contribute to the end goal (Pontoni, 2018). While the cause of the problem lies primarily in the regulatory landscape, it is this attitude that has tolerated the failure of existing waste management systems and our inability to achieve circularity.

Our society's utter reliance on petroleum-based goods and services, has allowed petroleum industry's forceful intervention in global politics, and has made it extremely difficult for governments or other regulatory bodies to provide impartial judgements/guidance More recent awareness driven by the private sector has led ruling bodies significantly closer to taking the measures toward solving our waste crisis. Immediate next steps must seek to recognize and incentivize use of materials that fulfill the criteria of the biological loop (at *both* the beginning and end of the product lifecycle). In light of the ever-more apparent repercussions, we must now learn from our mistakes and find ways to more carefully assess the impact of novel innovation without creating immense barriers to entry. It would be foolish to think petro-based and catalyst degradable additives do not deserve their place remainder of the 21st century, but use cases must be more carefully (re)considered before mass deployment to help preserve life on Earth.

References

A whopping 91% of plastic isn't recycled. (2018, December 20). Science. https://www.nationalgeographic.com/science/article/plastic-produced-recycling-waste-ocean-trash-debris-environment

Alamgeer, M. (2019). Polyhydroxyalkanoates (PHA) genes Database. Bioinformation, 15(1), 36–39. https://doi.org/10.6026/97320630015036

Allwood, J. M. (2014). Chapter 30 - Squaring the Circular Economy: The Role of Recycling within a Hierarchy of Material Management Strategies. In E. Worrell & M. A. Reuter (Eds.), Handbook of Recycling (pp. 445–477). Elsevier. https://doi.org/10.1016/B978-0-12-396459-5.00030-1

Barrett, A. (2018, July 5). The History of Bioplastics. Bioplastics News. https://bioplasticsnews.com/2018/07/05/history-of-bioplastics/

BioPreferred. (n.d.). Retrieved May 9, 2021, from https://www.biopreferred.gov/BioPreferred/faces/Welcome.xhtml

Conservation X Labs. (n.d.). Microfiber Innovation Challenge. Retrieved May 13, 2021, from https://www.microfiberinnovation.org

European Commission. Directorate General for the Environment. & Eunomia. (2016). The impact of the use of "oxo-degradable" plastic on the environment: Final report. Publications Office. https://data.europa.eu/doi/10.2779/992559

EUBIO_Admin. (n.d.). Oxo-Degradables. European Bioplastics e.V. Retrieved May 9, 2021, from https://www.european-bioplastics.org/bioplastics/standards/oxo-degradables/

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

Hess, D. J. (2014). Sustainability transitions: A political coalition perspective. Research Policy, 43(2), 278–283. https://doi.org/10.1016/j.respol.2013.10.008

How Big Oil Misled The Public Into Believing Plastic Would Be Recycled. (n.d.). NPR.Org. Retrieved May 9, 2021, from https://www.npr.org/2020/09/11/897692090/how-big-oil-misled-the-public-into-believing-plastic-would-be-recycled

January 09, & Lindwall, 2020 Courtney. (n.d.). Single-Use Plastics 101. NRDC. Retrieved May 9, 2021, from https://www.nrdc.org/stories/single-use-plastics-10

HSAC review of oxo-degradable plastics. (n.d.). 20.

OECD. (2013). Policies for Bioplastics in the Context of a Bioeconomy. https://doi.org/10.1787/5k3xpf9rrw6d-en

Oxo-Degradable Plastic Additives: Do These Additives Work? (n.d.). Retrieved May 9, 2021, from https://www.biosphereplastic.com/biodegradableplastic/oxo-degradable-plastic-additives-1254/

Polylactic Acid (PLA) Plastic. (2017, October 23). WhiteClouds. https://www.whiteclouds.com/3dpedia/pla.html

What Does Natural Mean? The FDA's New Definition Might Change Your Pantry | Bon Appétit. (n.d.). Retrieved May 9, 2021, from https://www.bonappetit.com/story/natural-food-definition