

Biocongruent Chemistry

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ABSTRACT

Sustainability in polymer systems requires balancing environmental responsibility with performance and economic viability. That is, industrial materials should be evaluated by their ability to balance functional durability with eventual environmental reintegration. In this work, sustainability is defined through three interconnected criteria: safety, circularity, and economic viability. While many durable polymeric materials achieve excellent performance through bioorthogonal molecular architectures that resist environmental degradation, these same characteristics can limit circularity and contribute to long-term persistence. To address this challenge, we introduce the concept of biocongruent chemistry, a design strategy that incorporates environmentally accessible molecular motifs into high-performance materials while preserving their functional properties during use. Biocongruent chemistry is the design of synthetic materials whose formation, function, degradation, and reintegration are congruent with biological and ecological cycling systems. Biocongruent materials contain environmentally accessible molecular motifs that permit eventual reintegration into natural biogeochemical cycles while maintaining useful service life. The framework of biocongruent chemistry is illustrated through a PIR foam system, in which biocongruent additives provided flame-retardant performance comparable to conventional halogenated flame-retardant additives while maintaining desirable foam physical properties, including mechanical performance and thermal conductivity.

INTRODUCTION

Sustainability in materials science is commonly evaluated through a combination of environmental, economic, and societal metrics, often quantified using tools such as life cycle assessment (LCA), carbon footprint analysis, resource efficiency, and end-of-life impact (Guinée 2016, Hauschild 2018). Widely cited frameworks emphasize concepts such as circular economy, green chemistry principles, and reduction of persistent environmental pollutants (Geissdoerfer 2017, Anastas 2000, Geyer 2017). However, these approaches often assess sustainability through isolated metrics, which may not fully capture the interplay between material performance, environmental compatibility, and economic viability. Manufacturers of sustainable materials must consider that despite increasing emphasis on recycling and circular economy frameworks, the accumulation of municipal solid waste (MSW) in landfills remains the most prevalent end-of-life strategy globally (Geyer 2017, Kazemi 2021). Consumers of any product, whether sustainable or not, will only purchase a product if they deem it economically advantageous. For example, customers perceive value when the product lasts a long time in use for the same, or lower, cost compared to a competitive product. Regulators and other legal authorities, whether before the sale (e.g. TSCA, FDA) or after the sale (e.g. EPA, tort litigators), will only allow a product in the marketplace if they deem it safe. For example, the product may need to demonstrate low carbon emissions or not contain banned substances (e.g. PFAS, TCPP).

To manufacture a sustainable product, therefore, three criteria must be met: the product must be safe, circular (preferably by a landfill pathway), and economic in the eyes of the customer (Figure 1). This is substantially the same definition of “cradle to cradle” sustainability first proposed by McDonough and Braungart, albeit with the substitution of “Equity” with “Economic” (McDonough and Braungart 2002). It is not enough for the product to solely be “biobased”, or to have biobased components and if it misses this definition of sustainability, in some regard it is not sustainable. A product will miss the sustainable mark either by the market, the regulatory environment, or because it fails to produce a truly circular economy when landfilled rather

than recycled. Biocongruent chemistry does not advocate landfilling. Rather, because landfilling remains the major disposal route, sustainable materials should be evaluated for their environmental behavior under landfill conditions.

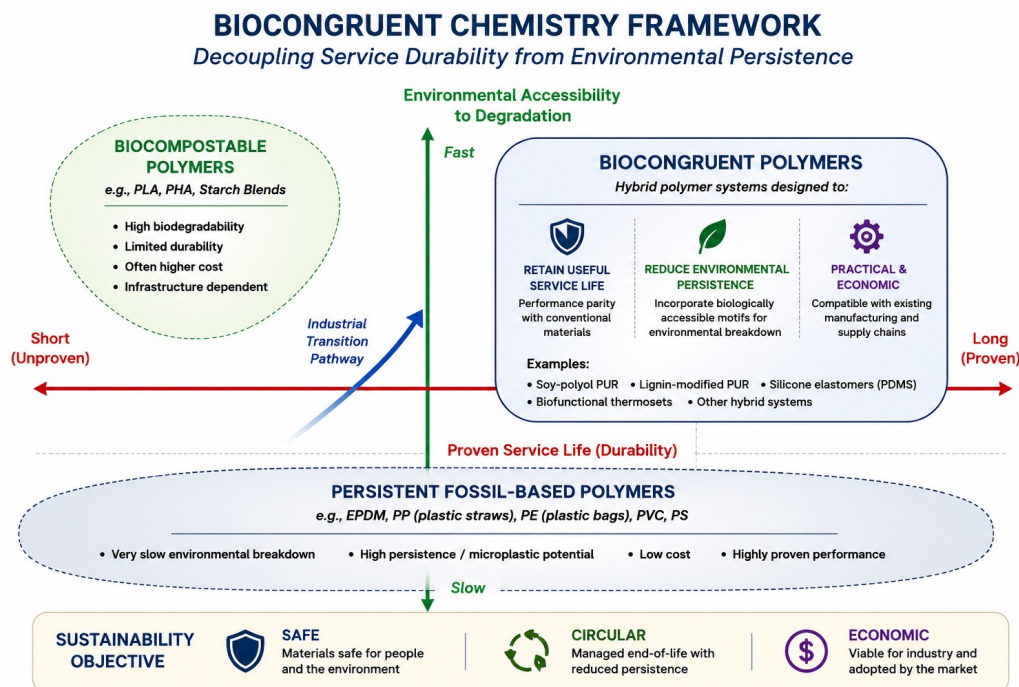


Figure 1. Biocongruent chemistry framework, as an approach to keep the (long) proven service life while reduce environmental persistence of polymers within the sustainability criteria of safety, circularity, and economic.

In order to achieve a sustainable material as described, we present the term “biocongruent chemistry” to include hybrid synthetic materials that have partly fossil-based and partly biobased or easy to degrade raw materials (Figure 2). The natural carbon cycle (e.g. bacterial, fungal and other biological pathways) allows such hybrid materials to undergo biological breakdown at faster rates compared to fully fossil-based synthetic materials. This synthetic approach allows manufacturers of successful fossil-based products to incorporate biobased raw materials at the additive levels (10%-15%). The resulting product can be tuned to maintain the desired performance during the service life and gain an advantage of (partial) sustainability.

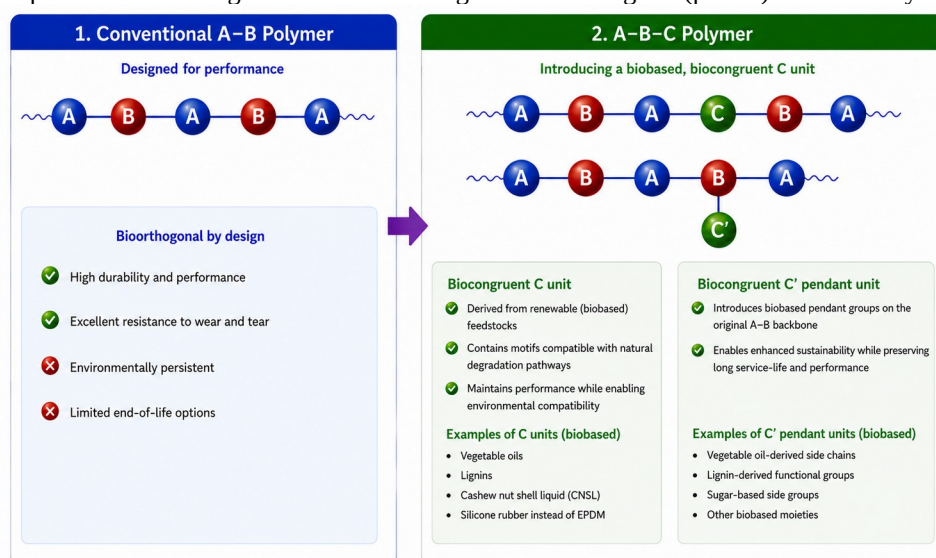


Figure 2. Incorporating biocongruent building blocks (C) into the matrix of a fossil-based polymer (AB).

EXPERIMENTAL

1) Soil-burial Degradation Study:

The biodegradation behavior of rigid polyisocyanurate (PIR) foam samples was evaluated through controlled soil burial experiments designed to simulate natural environmental exposure under both ambient and accelerated temperature conditions. Samples were prepared using different polyol compositions, including petroleum-based polyester polyol, 100% soy-based polyol, 40% soy-based polyol blend with 60% petroleum-based polyester polyol, and 40% lignin-based polyol blend with 60% petroleum-based polyester polyol formulations. All samples were fabricated into uniform cube specimens (1×1×1) cubes and cut to an average mass of 0.60 g prior to testing.

To evaluate the effect of accelerated aging, a parallel set of samples was incubated at an elevated temperature of 55 °C under identical soil and moisture conditions. In addition to mass loss measurements, the mechanical integrity of the samples was assessed following exposure. Compression testing was conducted to evaluate retention of mechanical properties relative to unexposed controls.

All samples were buried in a soil matrix at a depth of approximately 5 inches (≈12.7 cm). The soil moisture content was maintained at 37.7% to support microbial activity while avoiding saturation. Samples were incubated under ambient environmental conditions, and degradation was monitored over time through periodic retrieval and measurement of mass loss. Prior to weighing, samples were carefully cleaned to remove surface soil without disturbing the material surface. Mass loss was used as a primary indicator of degradation, calculated as the percentage reduction in sample mass over time. Mechanical performance retention was used as a secondary metric to assess the extent to which structural integrity was preserved during exposure. This combined approach enabled evaluation of both degradation kinetics and functional durability across different material systems and formulations.

II) Field Exposure Under Wastewater Treatment Plant Conditions Consistent with LA Green Book, landfill practices:

Biodegradation behavior of polyurethane (PU) foams incorporating soy-based polyols were previously evaluated under field conditions representative of wastewater treatment plant (WWTP). Sample exposures were conducted in accordance with standard landfill operational practices consistent with the City of Los Angeles Bureau of Engineering *Standard Specifications for Public Works Construction* (commonly referred to as the “LA Green Book”), which outlines the procedures (Engineering 2021). PU elastomer samples were embedded within active wastewater matrices achieve representative anaerobic conditions with very high BOD (~800 mg/L).

Samples were retrieved after 112 days of exposure. Following recovery, materials were gently cleaned to remove adhered waste without altering the structural integrity of the samples. Visual inspection was conducted to assess surface degradation, discoloration, and structural changes. Mechanical properties were evaluated by ASTM D412 methods and compared against unexposed control samples.

Despite observable signs of surface-level degradation, including discoloration and minor structural changes, the PU elastomers retained a substantial portion of their mechanical properties over the exposure period. These results suggest partial interaction with biologically active conditions while maintaining functional integrity, consistent with materials exhibiting biocongruent characteristics of biodegradation without meaningful loss of economic utility.

III) LCA (Cradle-to-Grave) on Silicone Rubber versus EPDM:

Streamlined comparative life cycle assessment (LCA) was conducted by LCA Design in accordance with ISO 14040 and ISO 14044 standards. The assessment compared EPDM and silicone elastomer heater hoses using a cradle-to-grave system boundary, which includes raw material extraction, polymer production, hose manufacturing, transportation, use, and end-of-life disposal.

The functional unit was defined as a 3/8” × 1 ft heater hose normalized to an equivalent reference service life under the intended operating conditions. Based on observed durability differences under the evaluated application conditions, three EPDM hoses were assumed to be required to provide the equivalent service life of one silicone hose.

The assessment used a comparative attributional modeling approach focused primarily on carbon footprint and cumulative energy demand. Primary manufacturing information was supplemented with secondary life cycle inventory datasets for upstream material production, transportation, and energy generation processes. End-of-life modeling assumed landfill disposal for both heater hoses.

RESULTS

We studied a case of biocongruent materials in a commercial PIR foam which was based on a fossil-based polyester polyol (OH value=295), using our soy-additive (A) (OH value 380), our phosphorylated soy-additive (B) (OH value 380,) and our modified lignin additive (C) (OH value 280) (Figure 3). Considering the main function of this PIR foam is in low temperature thermal insulation, we observed that replacing 10-15 parts of the original polyester polyol with our soy-additive (A) did not impact the thermal resistance of the foam (Figure 4). We also observed that some other mechanical properties of the foam such as yield load, yield stress at 10% load, density and foam characteristics (gel time, rise time, tack-free time) remained unchanged or changed very slightly by replacing our polyols (Table 1).

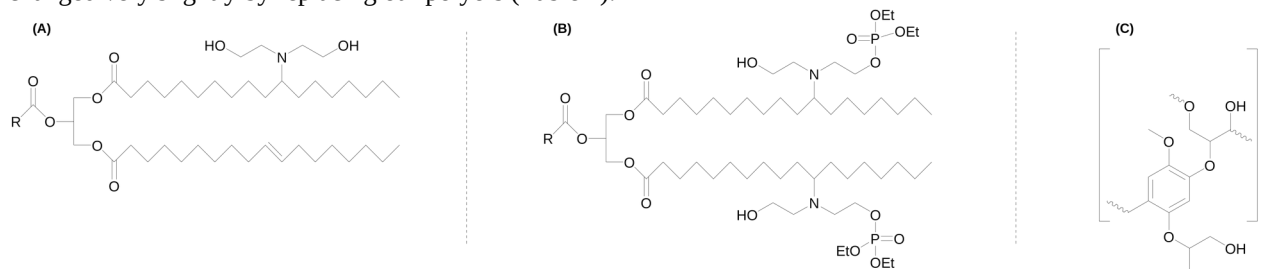


Figure 3. Soy-additive (A), phosphorylated soy-additive (B) and modified lignin additive (C).

The added benefit of using phosphorylated soy-additive (B) is its enhancement of flame retardancy in the PIR foam. Following the flame test of DN-4102 (B2 materials) was seen that replacing about 15 part of the original polyol with polyol (B) in this PIR foam is able to perform similar to 5 part of added TCPP to this foam (Figure 5, Table 2). With growing concerns about halogenated flame-retardant additives, this soy-additive is a sustainable and biocongruent solution as a replacement additive to TCPP. Similarly, lignin-based additive (C) was tested for mechanical property conservation in this foam and showed comparable mechanical and foam characteristics.

In a separate application, soy-additive (A) mixed with a non-halogenated phosphate flame retardant was used to replace parts of the polyol (polyether polyol) and the filler (CaCO_3) in a commercial polyurethane carpet backing. This application showed that by replacing 20 part of the combined polyol and the filler in the formulation, and applying the backing on a carpet sample, the resultant carpet showed similar flame resistance to a commercial class I carpet in a horizontal flame test using a custom-made radiant panel source similar to ASTM E648 (Figure 6). The flame test results show that the carpet with the backing that had 20 part of its polyol and filler (combined) replaced with soy-additive performed similar to a class I rated commercial carpet in terms of flame spread distance and flame out time (Table 3).

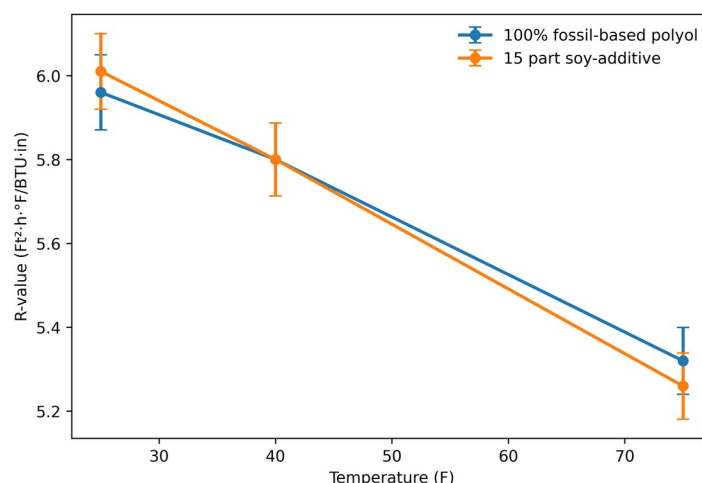


Figure 4. R-value of a commercial PIR foam with 100% fossil-based polyester polyol and 15 part polyol replaced with soy-additive (A).

Table 1. Physical and mechanical properties of soy-polyol, lignin polyol additives in PIR insulation foam.

	Yield Stress @ 10% Load (psi)	Yield Load (lb)	Density (lb/ft ³)	Gel time (s)	Rise time (s)	Tack Free time (s)
100% fossil-based polyester polyol	39.0 (±1.7)	155.9 (±6.0)	2.30 (±0.02)	1m	2m	4m

Table loss and spread PIR	100% fossil-based polyester polyol + 5 part TCPP	38.7 (± 1.2)	152.6 (± 4.3)	2.29 (± 0.02)	1m	2m	4m	2. Mass flame rate of samples
	10 part soy-additive (A)	42.3 (± 2.3)	163.9 (± 8.8)	2.29 (± 0.01)	58s	2m	3m 50s	
	15 part soy-additive (A)	38.0 (± 1.4)	145.1 (± 5.1)	2.28 (± 0.03)	55s	2m	3m 50s	
	15 part soy-additive (B)	40.7 (± 1.2)	167.6 (± 5.0)	2.32 (± 0.05)	56s	2m	3m 46s	
	15 part lignin-additive (C)	35.5 (± 2.8)	140.7 (± 6.1)	2.29 (± 0.03)	1m 5s	2m 5s	3m 15s	

containing soy-additive (B) and comparing their performance with TCPP

	Mass Loss (g)	Mass Loss (%)	Flame Spread Rate (cm/s)
100% fossil-based polyester polyol	0.85 (± 0.12)	8.4 (± 1.1)	0.38 (± 0.06)
100% fossil-based polyester polyol + 5 part TCPP	0.38 (± 0.06)	3.7 (± 0.5)	0.66 (± 0.15)
10 part soy-additive (B)	0.49 (± 0.02)	5.0 (± 0.2)	0.31 (± 0.03)
15 part soy-additive (B)	0.30 (± 0.05)	3.0 (± 0.1)	0.23 (± 0.03)

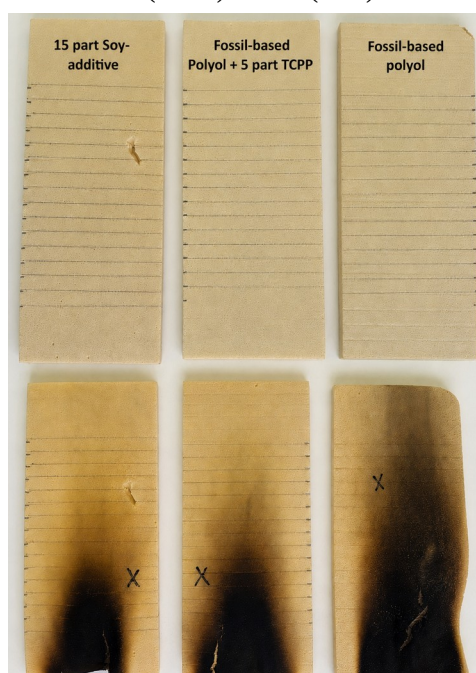


Figure 5. Flame resistant properties of the soy-additive (B) compared with the 100% fossil-based polyol

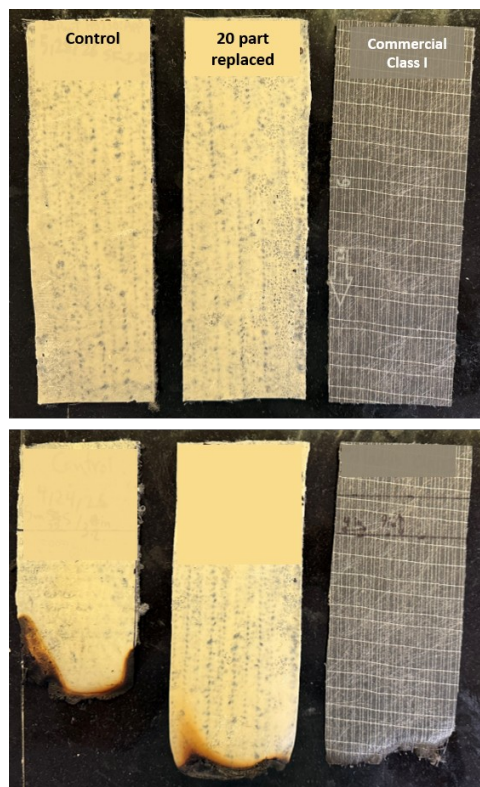


Figure 6. Flame resistant properties of the additive levels of blend of soy-additive (A) with a phosphate flame retardant for carpet backing application.

Table 3. Flame test results of carpets with PU backings compared to a class I rated commercial carpet.

	Flame Distance (cm)	Flame Out Time	Flame Spread Rate (cm/s)
Control (100% fossil based polyol)	9.27 (± 0.8)	5m 36s (± 25 s)	0.027
20 part polyol replaced	2.74 (± 0.2)	3m 4s (± 20 s)	0.015
Commercial class I carpet	2.54 (± 0.1)	2m 32s (± 23)	0.017

I) Soil-burial Biodegradation Study:

Samples of 100% fossil-based polyol, 100% soy-polyol and 40% replacement of the polyol with soy-polyol and lignin-polyol in a commercial PIR formulation were studied for gradual mass loss, when buried under soil under ambient condition and incubated at 55°C (Figure 7). Biocongruent foams containing soy-polyol and lignin-based polyols exhibited trends consistent with increased biodegradation relative to fully petroleum-based systems. This behavior suggests that both soy-polyol and lignin incorporation may promote biodegradation through enhanced compatibility with microbial and enzymatic pathways, while maintaining the structural and mechanical performance of the material (Table 1) Some mechanical properties such as maximum yield load and stress at 10% load remained relatively unchanged for these 40% soy-polyol similar to that of the 100% fossil-based polyol.

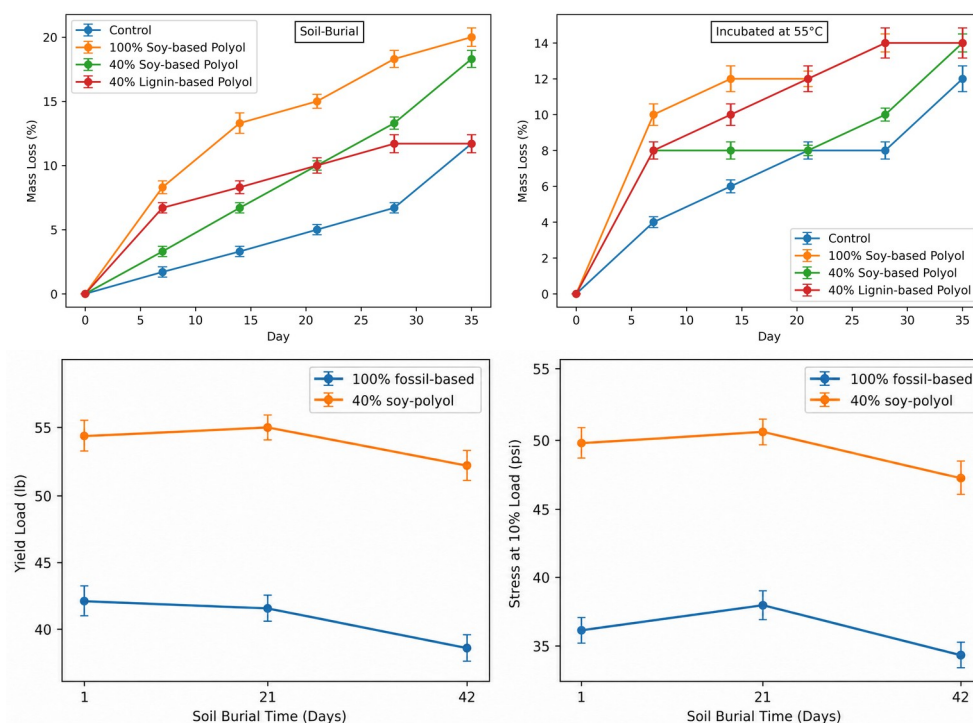
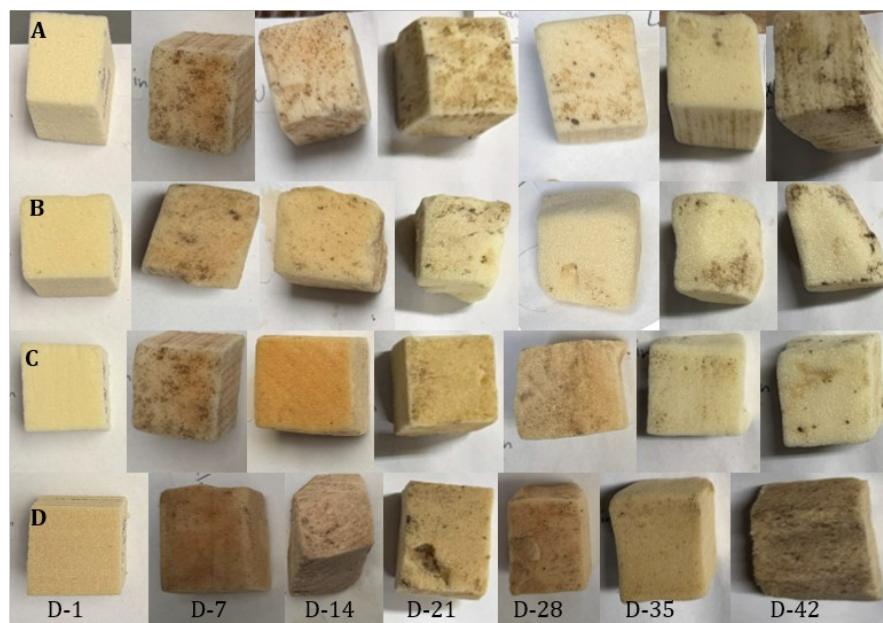


Figure 7. Biodegradation of PIR samples in a soil-burial over time of fossil-based polyester polyol (A), 100% Soy-polyol (B), 40% Soy-polyol (C) and 40% lignin-polyol (D). Mass loss (%) plots over 6 weeks of soil burial and 55°C incubation.

II) Field Exposure Under Waste Water Treatment Plant Conditions Consistent with LA Green Book, landfill practices:

Under field exposure conditions consistent with waste water treatment environments, elastomer polyurethane (PU) foams incorporating soy-based additives exhibited a unique combination of degradation behavior and mechanical stability. After 112 days of burial in urban waste water conditions, the materials showed measurable mass loss indicative of ongoing degradation processes. Despite this, the foams retained their tensile and compressive mechanical properties to a significant extent (Figure 8).

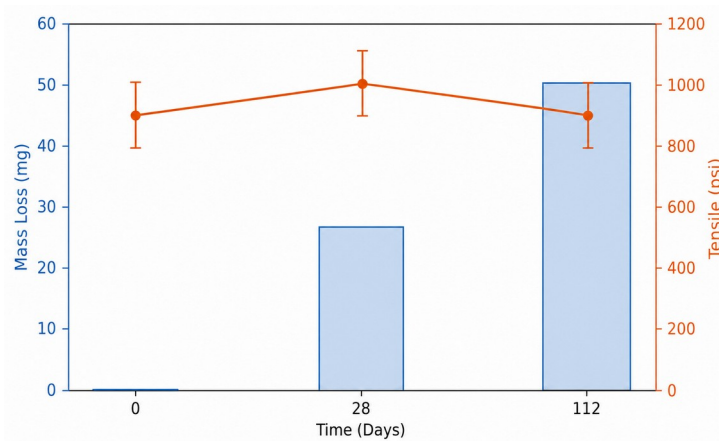


Figure 8. Soy-additive incorporated in PIR biodegradation under urban waste exposure

III) LCA (Cradle to Grave) on Silicone Rubber versus EPDM:

In this study, we performed a comparative LCA between a biocongruent silicone rubber heater hose and its bioorthogonal EPDM counterpart. Our results indicate that, on a per-unit basis, cradle-to-grave carbon footprint for both are of similar magnitude. Although EPDM hoses exhibited higher material mass and manufacturing energy requirements, silicone hoses demonstrated higher upstream material production impacts due to the energy-intensive processing associated with silicone precursor materials. At the individual product level, EPDM hoses consist of greater material mass and require higher manufacturing energy inputs relative to silicone hoses. However, silicone production involves energy-intensive upstream processing associated with silicon and siloxane precursor materials, contributing to comparatively higher embodied emissions during raw material production. To better understand the influence of durability assumptions on comparative performance, a sensitivity analysis was conducted on replacement frequency. When normalized to equivalent service life, the EPDM hose replacements required over the reference service period led to the cumulative carbon footprint associated with EPDM to be approximately three times greater than those associated with a single silicone hose providing equivalent functional performance (Figure 9).

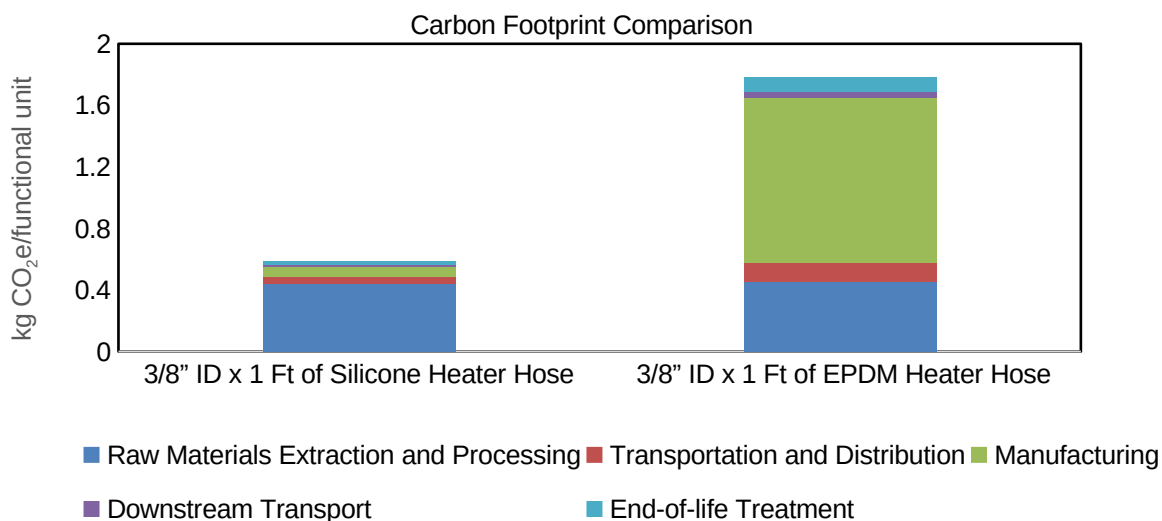


Figure 9. LCA analysis (cradle-to-grave) of silicone rubber heater hose and EPDM counterpart, considering about 1/3 durability factor for EPDM compared to silicone..

The assessment focused primarily on energy use and carbon footprint, where established LCA methodologies are most robust. Additional sustainability considerations, including environmental persistence, degradation behavior, microplastic generation potential, and material reintegration pathways, were evaluated qualitatively and discussed separately from the quantitative LCA

results due to current methodological limitations associated with modeling long-term environmental fate within conventional life cycle impact assessment frameworks.

Certain processes and impacts were outside the scope of the assessment, including capital equipment, infrastructure impacts, and detailed environmental fate characterization beyond standard end-of-life assumptions. Accordingly, the results should be interpreted as a comparative evaluation of relative environmental performance under the modeled conditions and assumptions.

DISCUSSION

In our context of safe-circular-economic sustainability framework, the concept of biocongruent chemistry has emerged as a useful strategy for evaluating material compatibility with natural biodegradation processes, while maintaining performance and the desired service life durability. Biocongruent materials are designed, or selected, to align with existing biochemical pathways in the biosphere, enabling their breakdown through widely available enzymatic and microbial mechanisms (Lucas 2008). We are using the term, “biocongruent chemistry” in deliberate contrast to the well-known “bioorthogonal chemistry”, which refers to chemical structures and reactions that do not naturally interact with, or are not recognized by, biological systems (Bertozzi 2011).

McDonough and Braungart have an alternate term for our synthetic approach, “monstrous hybrids”. With the greatest respect for these two pioneers in sustainable chemistry, we believe they erred in rejecting products that are created, in part from fossil fuels and part from biobased materials. Their concern was that such hybrids could not be recycled by either a technical mechanism (human recycling) or a biological one (the planet’s natural carbon cycle), therefore making such a hybrid non-circular and therefore not sustainable by a “cradle to cradle” definition of sustainability.

But polymers are not predictable. A predictable result would be the so-called, “Rule of Mixtures” (Reuss 1929). It implies that the physical properties of the mixture (e.g. modulus) will be some arithmetic combination of the physical properties of the two ingredients. In some cases it can happen, but it doesn’t usually appear a universal rule in polymeric materials. Consider degradation for instance. Two polymers in the blend can chemically stabilize one another, but they can also act to autocatalytically degrade each other (Mantia and et.al. 2017).

Biocongruent chemistry can use these principles to make fossil fuel polymers more biodegradable. Take, e.g. a simple fossil-based polymer: naturally occurring bacteria and fungi do not recognize its building blocks or molecular fragments. Thus, its degradation in a landfill will be limited to abrasion and similar physical processes. A fully bio-based polymer, on the other hand is often recognized by bacterial and fungal processes and can undergo premature degradation that can limit the service life of the product. A biocongruent polymer with additive levels of a bio-based monomer, might bring the best of both worlds and maintain the service life and intended properties, but also offer faster bio-degradation when it is landfilled. and the polymer has a higher probability of biodegrading (Figure 10).

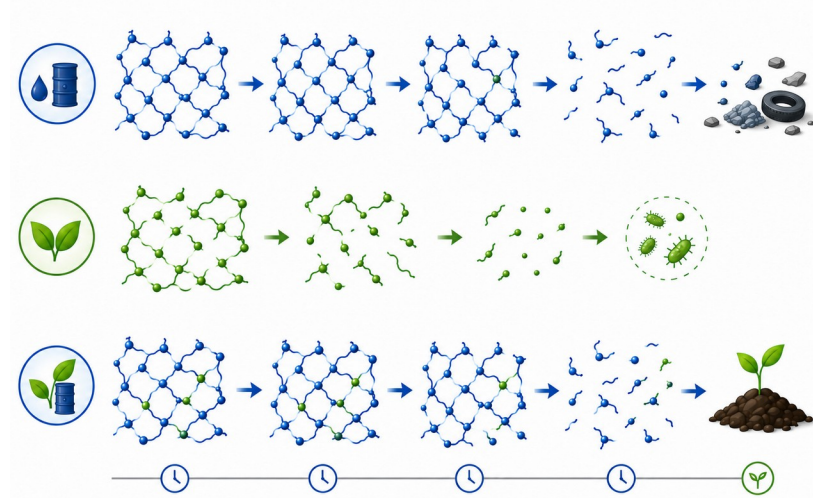


Figure 10. Relative biodegradation of the fossil-based (blue), bio-based (green) and biocongruent (blue-green) polymers.

Polymers are chains of monomers. So, often (but not always), they behave like chains. Say we have Polymer A, a heat stable material, and Polymer B, a chemically resistant polymer, and we mix them. We *don't* often get the best of both worlds, a heat

stable chemically resistant polymer. We can get the worst of both monomers, like any simple chain where the weakest link will give. So, if high temperatures make the Polymer A fall apart, the whole (co-polymerized) chain may fall apart. If a chemical challenge will make Polymer B fall apart, the whole (co-polymerized) chain may again fall apart.

It must be recognized that, unlike bioorthogonal chemistry, where there may be limited classes of chemical reactions that meet the definition, often with abiotic functional groups, there can be many paths to biocongruent chemistry. Some of them can be inorganic in nature. Indeed, other researchers have used biobased materials according to the synthetic scheme above (Q. Carboué 2022, H.S. Kim 2024). For instance, some abiotic polymers, like silicones (polydimethylsiloxanes) have been found to degrade in nature through hydrolysis by soil moisture (R.G. Lehmann 2000, D. Graiver 2003, Brook 2025). Therefore, PDMS exhibits environmental transformation pathways that support classification as a biocongruent material. So, as in bioorthogonal chemistry, where tests for cellular toxicity are performed to determine if the chemical reaction can occur inside of living systems, in biocongruent chemistry, tests for biodegradability are performed. The distinction between these two paradigms is particularly relevant for materials disposed in landfills, where biodegradation is mediated by diverse microbial consortia operating under dynamic environmental conditions (Shah 2008). Materials exhibiting biocongruent characteristics are more likely to undergo mineralization through established metabolic routes, contributing to biogas production in the form of carbon dioxide and methane (Cai 2023). Conversely, bioorthogonal materials tend to resist microbial attack, leading to long-term accumulation and potential environmental burden. Within landfill environments, waste undergoes a series of complex biological and chemical transformations, progressing from an initial aerobic phase to predominantly anaerobic, methanogenic conditions as oxygen becomes depleted (Tokawa 2009, Eleazer 1997). These sequential stages govern the degradation pathways and ultimate fate of the disposed materials in landfills.

We also argue that it is critical to adjust the cycle speed of biodegradability by controlling the relative amount of the bio-based units in the polymer matrix. From commercial standpoint, the lifespan of a product can compensate for its fossil-based nature as in the case of PFAS coatings that were used to obtain LEED Platinum certification in buildings. From other perspectives, when very long lifespans are expected, merely a bio-based solution is often not an attractive solution for the market. Often planned obsolescence and sustainability are, as commercial models, in opposition. Alternatively in such case we can design the biocongruent material in a way that the additive group (C) carries a pendant bio-based group, that will biodegrade more rapidly without compromising the lifetime and service properties of the product. So, we can achieve a biocongruent material by pursuing three synthetic strategies:

- The chemical composition of the C group, and how it interacts with A and B. They can chemically stabilize, or destabilize, one another, or the hybrid can behave as a “rule of mixtures”.
- The concentration of the C functional groups. Perhaps a higher concentration of C will biodegrade faster.
- The possibility of a C' group, where pendant mass could biodegrade quickly, providing some “quick wins” in circularity, but without (significantly) impacting the lifetime of the product.

This phenomenon was observed in our results. In the biodegradation experiment based on PIR samples in soil-burial study, PIR samples of a commercial formulation were found to biodegrade in landfill environments. In addition, the economic performance of the material was improved. The flame resistance of the final foams increased (Figure 5), while maintaining the physical characteristics of the foams such as yield stress at 10% load and the yield load. In the second application, a mixture of soy-additive (A) and a phosphate flame retardant was used in replacing parts of the polyol and filler in a carpet backing formulation. The resultant carpet showed similar flame resistance to a class I rated carpet in the horizontal flame test under radiation heat. The incorporation of lignin-based additives further extended these sustainability attributes. Lignin, an abundant byproduct of the pulp and paper industry, represents a highly underutilized renewable resource with significant potential for value-added material applications. Its aromatic structure and functional group diversity enable its incorporation into polyurethane networks, while also introducing chemically accessible sites that may enhance interaction with environmental degradation processes.

In order to magnify the effect of incorporating soy-additive and lignin-additive in biodegradation of the PIR foams, samples of 100% fossil-based polyol, 100% soy-polyol and 40% replacement of the polyol with soy-polyol and lignin-polyol were studied that is higher than typical additive levels. In the soil burial biodegradation study of PIR samples, formulations containing soy-polyol and lignin-based polyol exhibited trends consistent with increased degradation relative to fully petroleum-based systems. This behavior suggests that both soy-polyol and lignin incorporation may promote biodegradation through enhanced compatibility with microbial and enzymatic pathways, while still contributing to the structural performance of the material. From the perspective of the proposed sustainability framework, lignin-based additives offer advantages in circularity through waste valorization, safety through natural origin, and economic benefit by leveraging low-cost industrial byproducts. From the perspective of the proposed sustainability framework, lignin-based additives offer advantages in circularity through waste valorization, safety through natural origin, and economic benefit by leveraging low-cost industrial byproducts from pulp and paper industry.

In a second degradation case study, PU samples containing soy-additive (A) were exposed to wastewater treatment plant condition and monitored for mass loss and mechanical properties over a period of about 3 months. The conservation of the mechanical properties in this study suggests that degradation occurred without immediate compromise of structural integrity. This apparent decoupling between mass loss and mechanical performance indicates that degradation is likely localized to specific chemically accessible domains within the polymer network, particularly those associated with soy-based additive segments. The preservation of bulk mechanical properties suggests that the crosslinked network structure remains largely intact during early stages of degradation, enabling continued functional performance even as material breakdown is initiated.

(Bio)degradation timescales are an important consideration when evaluating the sustainability of polymeric materials. Composability standards such as ASTM D6400, ASTM D6868, and EN 13432 define compostable materials as those that rapidly degrade under controlled conditions, typically requiring at least 90% conversion to carbon dioxide within 180 days and less than 10% residual material greater than 2 mm after 12 weeks at elevated temperature (~58°C), controlled moisture, and active microbial activity (Russel and et.al. 2014). While these standards provide a useful benchmark, rapid degradation is not a prerequisite for sustainability. Natural materials such as wood may require 10–200 years to decompose, depending on species and environmental conditions, yet forests remain sustainable because biomass production balances removal and decomposition. This suggests that sustainability depends less on the absolute rate of degradation than on the balance between material generation, use, and environmental recycling.

In a circular system, the quantity of material in use and recycling should remain small relative to the total mass available within the natural cycle. Under these conditions, long-lived materials can remain compatible with circularity despite extended degradation times. This makes silicon, the second most abundant element on our planet, and carbon, our most biologically dominant element, both excellent candidates for biocongruent chemistry. Accordingly, biocongruent chemistry is not defined by rapid biodegradation, but by designing materials with service lifetimes appropriate to their application while maintaining compatibility with natural transformation pathways at end-of-life. From this perspective, both carbon- and silicon-based materials are attractive platforms for biocongruent design because they participate in abundant natural cycles. Their sustainability depends not only on degradation rate, but also on how effectively they integrate into those cycles over time.

There can be multiple synthetic pathways to a biocongruent material. The hybrid PU elastomers (carpet backing) and PIR foams described above is one methodology. Selecting materials, even abiotic ones such as PDMS (silicone), that biodegrade are also viable within biocongruent chemistry framework. But, to be economically efficient, a biocongruent material must provide either an economic benefit in cost or performance (such as being long lasting in service). Contribution analysis in the LCA study of EPDM vs silicone heater hose indicated that upstream raw material production represented the dominant source of carbon footprint for silicone materials, whereas manufacturing energy contributed a larger relative share of impacts for EPDM hoses. Transportation impacts were comparatively minor for both systems under the modeled conditions. However, when normalized to equivalent service life, the EPDM hose replacements required over the reference service period led to the cumulative carbon footprint associated with EPDM to be approximately three times greater than those associated with a single silicone hose providing equivalent functional performance (Figure 9). These results demonstrate the importance of durability and replacement frequency in biocongruent elastomer product assessments. While silicone materials may exhibit higher embodied impacts during initial material production, longer service life offset these burdens through reduced replacement requirements and associated manufacturing impacts. From a broader sustainability perspective, the analysis suggests a trade-off between upstream production impacts and long-term service performance. EPDM benefits from established manufacturing infrastructure and comparatively lower upstream material production impacts, while silicone offers advantages associated with extended durability and differing end-of-life degradation behavior.

Taken together, the results demonstrate that material selection outcomes may vary depending on whether evaluation criteria prioritize initial production emissions, or lifetime service emissions, as well as long-term environmental fate considerations. Integrating these factors remains an important area for future development in sustainability assessment methodologies for elastomeric products.

CONCLUSION

This work introduced biocongruent chemistry as a framework for designing sustainable polymeric materials based on three interconnected criteria: safety, circularity, and economic viability. Rather than emphasizing rapid biodegradation alone,

biocongruent chemistry seeks to balance material performance and durability with compatibility with natural environmental transformation pathways at the end-of-life state of a material.

Polyurethane systems containing soy- and lignin-based additives exhibited enhanced biodegradation behavior while retaining mechanical properties and thermal resistance demonstrating that biobased components can improve environmental accessibility without sacrificing performance in PIR samples. In addition, life cycle assessment showed that silicone rubber heater hoses can provide lower lifetime carbon footprints than EPDM alternatives when normalized to equivalent service life, highlighting the importance of durability in sustainable material design.

Overall, these results demonstrate that sustainability must be evaluated across the entire product life cycle. The biocongruent chemistry framework provides a practical approach for developing materials that meet performance requirements and can be designed to add or enhance new performance while remaining compatible with natural recycling and transformation processes.

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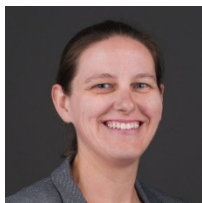
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BIOGRAPHIES

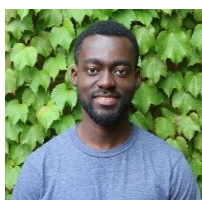


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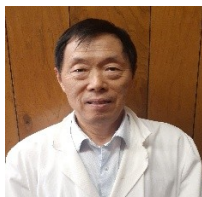
Saeed has been working on synthesis and formulation of fire-retardant additives for polyurethane formulations since joining MCPU.



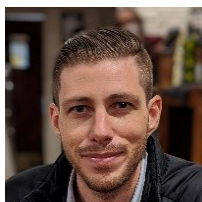
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