Challenges in substituting fossil products with bio-based alternatives

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1. Introduction

Bio-based products hold the potential to improve the environmental performance and enable greater circularity in European and global sector, bringing several direct and indirect benefits such as sustainable management of natural resources, reducing the dependence on non-renewable resources, mitigating climate change, and strengthen European competitiveness [1,2]. To grow bio-based sectors, it is however necessary to substitute current fossil-based products and other incumbent products with their bio-based alternatives. In this regard, deeper scientific knowledge to understand the ecological boundaries of the bioeconomy is still needed, as well as it is increasingly necessary to perform a proper life assessment of the environmental sustainability and circularity of bio-based products in a life cycle perspective, to ensure that their performance is effectively better than the incumbent alternatives. In this context, previous studies suggest that substituting current products with bio-based ones might not be without challenges [3]. For example, differences in the technical performance, the regulatory framework, or the user behaviour might complicate or make meaningless such comparison, unless these specific conditions are explicitly considered in an LCA study.

2. Materials and Methods

We here investigate substitution effects, intended as to what extent and on which bases bio-based and fossil-based are comparable and substitutable and if they provide equal functionality, for a range of cases. We address how existing LCA studies have described substitution effects (Vadenbo et al. 2017) through a mixed methods approach that includes the review of scientific literature as well as a survey of key stakeholders from the LCA4BIO project stakeholder's group as well as sector representatives. The systematic analysis focused on comparing specific technical functionalities (e.g., tensile strength of wood vs. concrete), product longevity and lifetime replacement rates, institutional and regulatory requirements. The presentation at SETAC focuses on the systematic review as the survey results will not yet be available at the time of the conference. The systematic review focused on analysing challenges associated with the substitution of fossil-based into bio-based materials across five different sectors: construction, packaging, textiles, chemicals, and woodworking. Overall, 42 peer-reviewed articles were selected based on their relevance to the bio-based substitution in those sectors. To find these relevant articles, initially, the Google Scholar database was searched with the phrase “fossil-based vs bio-based” followed by the sector name (e.g., “fossil-based vs bio-based construction”). Only those articles that were specifically focused on the substitution of fossil-based products with bio-based alternatives were then considered. Next, the considered article was analysed via the AI-based tool Research Rabbit to identify related publications. The 42 peer-reviewed articles examined in this study addressed a wide range of challenges related to the adoption of bio-based substitutes. Performing the analysis across five sectors allowed us to get an overall understanding of the substitution challenges as well as common themes.

3. Results

We summarize here the key challenges in replacing fossil-based products with bio-based alternatives across five sectors: construction, packaging, textiles, chemicals, and woodworking. These are preliminary results while more complete results will be presented at the conference.

In construction, the main challenges relate to the mechanical properties and durability of the bio-based materials replacing traditional ones, such as wood and plant-based insulation. While Cross-Laminated Timber (CLT) is an excellent substitute for fossil-based materials, it needs additional treatments for fire resistance, like fireproof coatings or gypsum board to comply with building codes. Moreover, the use of wood for high-rise buildings is complicated by fire safety regulations in some countries that limit its use as a load-bearing material for structures above four stories. Durability issues of wood, such as UV degradation, moisture, and biological damage (e.g., fungi or insects), require additional protective coatings to ensure longevity. Furthermore, bio-based insulation, such as meadow grass, generally has higher thermal conductivity compared to mineral insulation, meaning that it requires thicker layers of insulation to achieve the same thermal performance.

Additionally, acoustic performance is also a concern for bio-based materials such as CLT, which often require soundboards or insulation to meet noise standards.

In the packaging sector, the main challenges that bio-based alternatives face are mechanical properties. The suitability of some bio-based materials (e.g., natural biopolymer films) for packaging is limited because they can become unstable in humid environments or when in contact with high-moisture food. Moreover, some bio-based materials, such as bioplastic are more expensive than traditional plastic and some of them need special conditions to biodegrade, which complicates the waste management. Seasonal variations in the supply of raw materials, like corn starch, can affect production continuity. To improve qualities like moisture resistance, bio-based materials are occasionally coated with synthetic polymers, which makes recycling more challenging.

In the textile sector, challenges occur in the processability area. Bio-based textiles can be more difficult to process compared to synthetic fibres, hence they are less competitive in mass production. Moreover, textiles made from bio-based materials, such as algae, may experience colour fading over time. Production of biopolymers requires different production processes, challenging suppliers who cannot utilize the same machinery as for synthetic materials.

In the chemicals sector, the main challenges with the substitution are availability and transportation. Although biomass feedstocks are renewable, they are limited by the seasonal availability. Compared to fossil-based feedstock, biomass has a higher water content and a lower bulk density, which increases transportation costs. Moreover, biorefinery faces challenges associated with separating major components of biomass (such as cellulose, lignin, etc.). Additionally, if the moisture content of some bio-based materials, such as straw, rises above a certain level, they may begin to ferment, lowering the raw material's quality.

In the woodworking sector, major challenges when using bio-based alternatives are related to the mechanical properties. Bio-based materials have high prices, slow reaction time, and too short pot life when compared to fossil-based materials. Moreover, the glue strength and water resistance of the bio-based adhesives are limited. Additionally, there is a higher risk of a chemical reaction when mixing bio-based adhesives with other chemicals, which can reduce the strength of the final product.

4. Conclusions

The main highlight from this work is that substituting fossil-based products with bio-based ones presents challenges that vary depending on material properties and regulations and sector of application. The next step (currently ongoing) will be a survey with the LCA4BIO project stakeholder network, producers and actors in the emerging bio-based sectors as well as consumers, to reveal their attitude towards bio-based products, to what extent they consider these substitutable to their fossil counterparts, key technical functionalities of both, any institutional restrictions (e.g., standards obliging certain amounts to be used) and challenges and opportunities they experience when substituting fossil products with bio-based ones. A collection of key examples, best practices, and recommendations will be provided that can be used for further guidance in bio-based product development, marketing, and concretely in the LCA modelling - specifically when defining functional unit and system scope in comparative LCA studies of fossil- and bio-based products.

5. References

[1] Zuiderveen, Emma A. R., Koen J. J. Kuipers, Carla Caldeira, Steef V. Hanssen, Mitchell K. van der Hulst, Melinda M. J. de Jonge, Anestis Vlysidis, Rosalie van Zelm, Serenella Sala, and Mark A. J. Huijbregts. 2023. "The Potential of Emerging Bio-Based Products to Reduce Environmental Impacts." *Nature Communications* 14(1):8521. doi: 10.1038/s41467-023-43797-9.

[2] Sevigné-Itoiz, Eva, Onesmus Mwabonje, Calliope Panoutsou, and Jeremy Woods. 2021. "Life Cycle Assessment (LCA): Informing the Development of a Sustainable Circular Bioeconomy?" *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 379(2206):20200352–20200352. doi: 10.1098/rsta.2020.0352.

[3] Rinke Dias de Souza, Nariê, Marisa Groenestege, Jurjen Spekreijse, Cláudia Ribeiro, Cristina T. Matos, Massimo Pizzol, and Francesco Cherubini. 2024. "Challenges and Opportunities toward a Sustainable Bio-Based Chemical Sector in Europe." *WIREs Energy and Environment* 13(4):e534. doi: 10.1002/wene.534.

[4] Vadenbo, Carl, Stefanie Hellweg, and Thomas Fruergaard Astrup. 2017. "Let's Be Clear(Er) about Substitution: A Reporting Framework to Account for Product Displacement in Life Cycle Assessment." *Journal of Industrial Ecology* 21(5):1078–89. doi: 10.1111/jiec.12519.

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