View on Life Cycle Assessment of Bioplastics Synthesis from Lignocellulose

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Nowadays, plastics offer a broad range of indispensable applications, including construction materials, lightweight engineering, adhesives, microelectronics, biomedical materials, and packaging of all kinds of goods (Isikgor & Becer, 2015). Global production has reached 370 million tons in 2018, but this dependency is currently unsustainable, having ecological, societal, and economic consequences (Rouch, 2021). Synthetic polymers' degradation rate is slow, which means that without appropriate waste management systems, macro and microplastics waste accumulates in the environment, with significant burdens on living organisms and ecosystems reverberating for years (Ali et al., 2021). Their extended life suggests that the full proportions of plastic impacts on the environment are not completely understood and may even be underestimated (Ali et al., 2021). One thing is clear: the urgent need to replace conventional plastics with new biodegradable materials (Karan et al., 2019).

Lignocellulosic biomass, commonly found in plants and algae, is the most abundant and renewable source of natural polymers on the planet, notably cellulose, hemicellulose, and lignin (Nanda et al., 2013). These polymers can also be synthesized at the nanoscale in biorefineries from monomers derived from biomass and be used as fillers in a matrix. This will result in biodegradable and biocompatible materials with enhanced traits that can potentially be a substitute for plastics. Bioplastics may have a fundamental role in the transition towards a low carbon circular economy, potentially dismissing worrisome carbon emissions and waste management that arise from the production of synthetic polymers from finite fossil resources. Furthermore, valuable chemicals can be obtained from lignocellulose. Despite the evident advantages of lignocellulosic biomass, its conversion into the desired product is complex, due to its recalcitrant behaviour. Thus, various extraction methods or routes can be used, requiring different material and energy inputs that can cause some strain on the environment. The overall environmental benefits of such emerging bio-based compounds are yet to be understood. To clearly understand the overall environmental impact of such developments, Life Cycle Assessment (LCA) can be used. Nevertheless, contradicting results can be found. Thus, in order to systematize the existing knowledge, this study proposes a review of the main biorefinery processes from an LCA perspective.

The LCA methodology includes the goal and scope definition phase; life cycle inventory analysis (LCI); the environmental impact assessment phase (LCIA) and the interpretation phase (ISO, 2006). In the first phase, the purpose of the study is defined. In the LCI, input and output data of the system are collected. The LCIA gives additional information regarding environmental impacts and, in the last phase, conclusions from the study are provided. At the end of the life cycle analysis, potential hotspots of the system can be predicted, allowing practitioners to indicate which procedures should be improved. The conclusions of any given subject are more reliable the more LCA studies are conducted and the more comprehensive (*e.g.*, cradle-to-cradle) they are (Fantin et al., 2014).

Forest and agricultural residues, generated from agricultural and industrial activities, are an important source of lignocellulosic biomass that can be used as feedstock in biorefinery processes. Collecting these sources of biomass is at the beginning of the value chain, where the next step is biomass treatment. Biomass can be physically, chemically, or biologically pretreated. The most standard methods of fractionating biomass are the sulfite and kraft process, known for their role in the pulp and paper industry. Other treatments include milling, microwave irradiation, mechanical extrusion, pyrolysis, pulse electric field, acid/alkali pretreatment, ozonolysis and ammonia fiber expansion (Muhammad Nauman, 2019). More recently, attention has been given to organosolv and hydrothermal, as more sustainable pretreatments (Zhang et al., 2020). Organosolv, generally, uses organic acids or alcohols as solvents, aided or not by a catalyst, to fractionate biomass. Alternative solvents, such as Ionic Liquids or Deep Eutectic Solvents have also been given attention (Smith et al., 2014). Hydrothermal, in turn, requires no chemicals, as water at high temperatures behaves as an acid powerful enough to achieve the same goal. An appropriate selection and optimization of the pretreatments are essential to maximize the product's yield and quality, while also reducing energy and water requirements and wastes. In this context, LCA is a useful methodology to assess the strains caused by pretreatment conditions and chemicals used and to look out for emergent alternatives.

After pretreatment, and once individual lignocellulosic fractions are obtained, distinct strategies may be applied in order to go from intermediate to final product. From polymeric cellulose, for example, cellulose monomers and then nano-fibrillated cellulose (CNF) or cellulose nanocrystals (CNC) can be produced. CNF may be generated via mechanical treatments, such as ultrasonication and homogenization, while CNC is fabricated by chemical treatments, such as acid hydrolysis. Cellulose and hemicellulose can also be submitted to enzymatic hydrolysis to produce mono or oligosaccharides, namely bacterial nanocellulose (BNC) (Thomas et al., 2018). Lignin, the most abundant aromatic polymer in the world, is usually burned to generate power and heat in biorefineries. However, the lignin treatment using the described techniques is a more sustainable method to valorize this biomass fraction (Jawaid & Abdul Khalil, 2011). Lignin can be converted into nano-lignin, to be used as filler in biomaterials, or in valuable products, e.g., vanillin (Upton & Kasko, 2016). Applying a combined pretreatment of biomass using both hydrothermal and organosolv methods effectively results in high-purity lignin, allowing the valorization of other lignocellulosic segments (Michelin et al., 2018).

To date, few LCA studies have been performed on this matter, and most of them are cradle-to-gate. The main data is obtained at the laboratory level and, thus, it is difficult to transpose to an industrial scale. However, in existing studies, it is possible to observe that, even when working with something as seemingly harmless as biomass, the treatments used to obtain the final product are not always environmentally friendly. High energy requirements and costs, intensive use of chemicals, and high-water consumption are some of the issues registered. Therefore, it is essential to develop more ecological and economical solutions. In order to understand exactly the effects of these processes, it is imperative to develop more comprehensive LCA studies in larger quantities. That is the way to undoubtedly prove that biopolymers are, indeed, a viable and sustainable alternative to synthetic polymers (Piccinno et al., 2018).

Author Contributions

Conceptualization, D.S. and L.S.; Data curation, D.S. and L.S.; Formal analysis, H.M., B.M. and J.A.; Funding acquisition, H.M.; Methodology, D.S. and L.S.; Project administration, H.M.; Resources, H.M.; Supervision, H.M., B.M. and J.A.; Validation, H.M., B.M. and J.A.; Writing—original draft, D.S. and L.S.; Writing—review & editing, D.S., L.S., H.M., B.M. and J.A. All authors have read and agreed to the submitted version of the abstract.

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