Life Cycle Assessment of Agro-Waste Valorisation into Bioplastics and Bio-stimulants within a Circular Economy

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ABSTRACT

Agro-waste valorisation is emerging as a high-value strategy to reduce agricultural residues while replacing fossil-based plastics and synthetic agrochemicals. Converting crop residues into bioplastics and plant bio-stimulants aligns with circular economy goals by closing material loops and reducing waste. This article summarizes life cycle assessment (LCA) findings on these pathways, highlighting environmental benefits, key trade-offs, and design considerations for integrated biorefineries. Overall, agro-waste-derived products offer significant potential for lowering greenhouse gas emissions and resource use, though results depend strongly on system boundaries, energy supply, and allocation methods.

INTRODUCTION

Agriculture generates millions of tonnes of residues annually-straws, husks, fruit pomace, and processing sludges-many of which are burned or landfilled. At the same time, plastic pollution and chemical-intensive farming demand sustainable alternatives. Transforming agro-waste into bioplastics (*e.g.,* PLA, PHAs) and bio-stimulants provides a dual benefit: reducing waste and creating renewable, low-impact materials. Life cycle assessment is essential for verifying whether these solutions

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truly outperform conventional plastics and fertilizers.

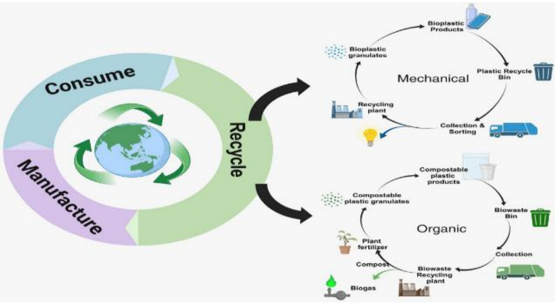

Figure 1: LCA for bioplastic and bio-stimulant production

Circular Economy Perspective

A circular economy aims to maximize resource efficiency by keeping materials in continuous use. Agro-waste fits this model by serving as a renewable feedstock for multiple bioproducts. Bioplastics reduce fossil-carbon dependence, while bio-stimulants enhance nutrient use efficiency and soil health. The circular benefits are amplified when residues are genuinely surplus and when conversion processes are powered by renewable energy.

LCA Methodology for Agro-Waste Valorisation

LCA follows ISO 14040/44 and includes four phases: goal and scope, inventory, impact assessment, and interpretation.

Key considerations include:

- **Functional unit:** Typically, 1 kg bioplastic or 1 L/kg bio-stimulant applied per hectare.
- **System boundaries:** Cradle-to-gate (production only) or cradle-to-grave (including use & end-of-life).
- **Impact categories:** Global warming potential, energy demand, eutrophication, acidification, and resource depletion.
- **Hotspots:** Pretreatment energy, chemical use, transportation, and end-of-life emissions.

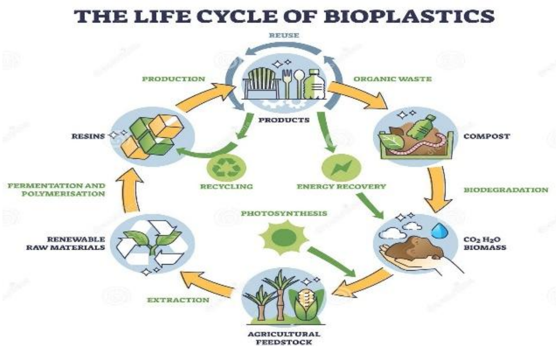

Figure 2: Life cycle of bioplastics

LCA Findings: Bioplastics from Agro-Waste

LCA studies indicate that agro-waste-derived bioplastics generally have **lower greenhouse gas emissions and fossil resource use** compared to PE, PP, or PET plastics. Benefits improve when:

- Waste is treated as a true by-product,
- Renewable energy powers fermentation and polymerization,
- End-of-life includes composting, recycling, or energy recovery.

Trade-offs include

- Higher energy demand during pretreatment and fermentation,
- Potential eutrophication burdens (depending on how agricultural impacts are allocated),
- Uncertain biodegradability outside industrial composting conditions.

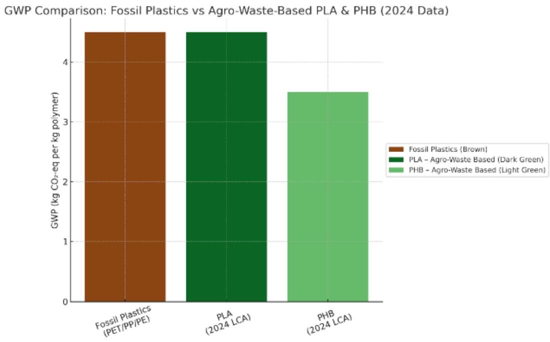

Figure 3: GWP comparison chart of fossil plastics vs. agro-waste-based PLA/PHB

LCA Findings: Bio-stimulants from Agro-Waste

Bio-stimulants produced from fruit residues, vegetable waste, microbial cultures, or algal biomass can significantly reduce fertilizer demand. LCA results show improvements in climate impact and resource use when bio-stimulants replace synthetic inputs or enhance crop yields. However, production hotspots include drying, extraction, substrate preparation, and field emissions (e.g., N_2O), which require careful modelling.

Integrated Biorefineries: Maximizing Circularity

Modern approaches combine bioplastic, bio-stimulant, and bioenergy production in a single biorefinery. These integrated systems can reduce environmental impacts by:

- Sharing energy and materials across processes,
- Turning side-streams (*e.g.*, biochar, digestate) into valuable soil conditioners,
- Eliminating waste disposal.

LCA studies show improved climate performance and strong economic feasibility, though multifunctionality introduces methodological complexities.

Challenges and Recommendations

Challenges:

- Allocation of agricultural impacts between crops and residues,
- Data gaps at industrial scale,
- Uncertain end-of-life scenarios and soil emission factors.

Recommendations:

- Use harmonized LCA practices with transparent assumptions,
- Prioritize truly surplus residues,
- Integrate renewable energy and low-impact pretreatment,
- Design biorefineries that valorise all streams,
- Include soil health and circularity benefits in assessments.

CONCLUSION

Agro-waste valorisation into bioplastics and bio-stimulants offers a promising circular economy pathway that reduces waste, decreases reliance on fossil resources, and promotes sustainable agriculture. LCA evidence supports significant environmental benefits, especially when processes are energy-efficient and residues are responsibly sourced. Integrated biorefineries represent the next step toward fully circular bio-based material systems.

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