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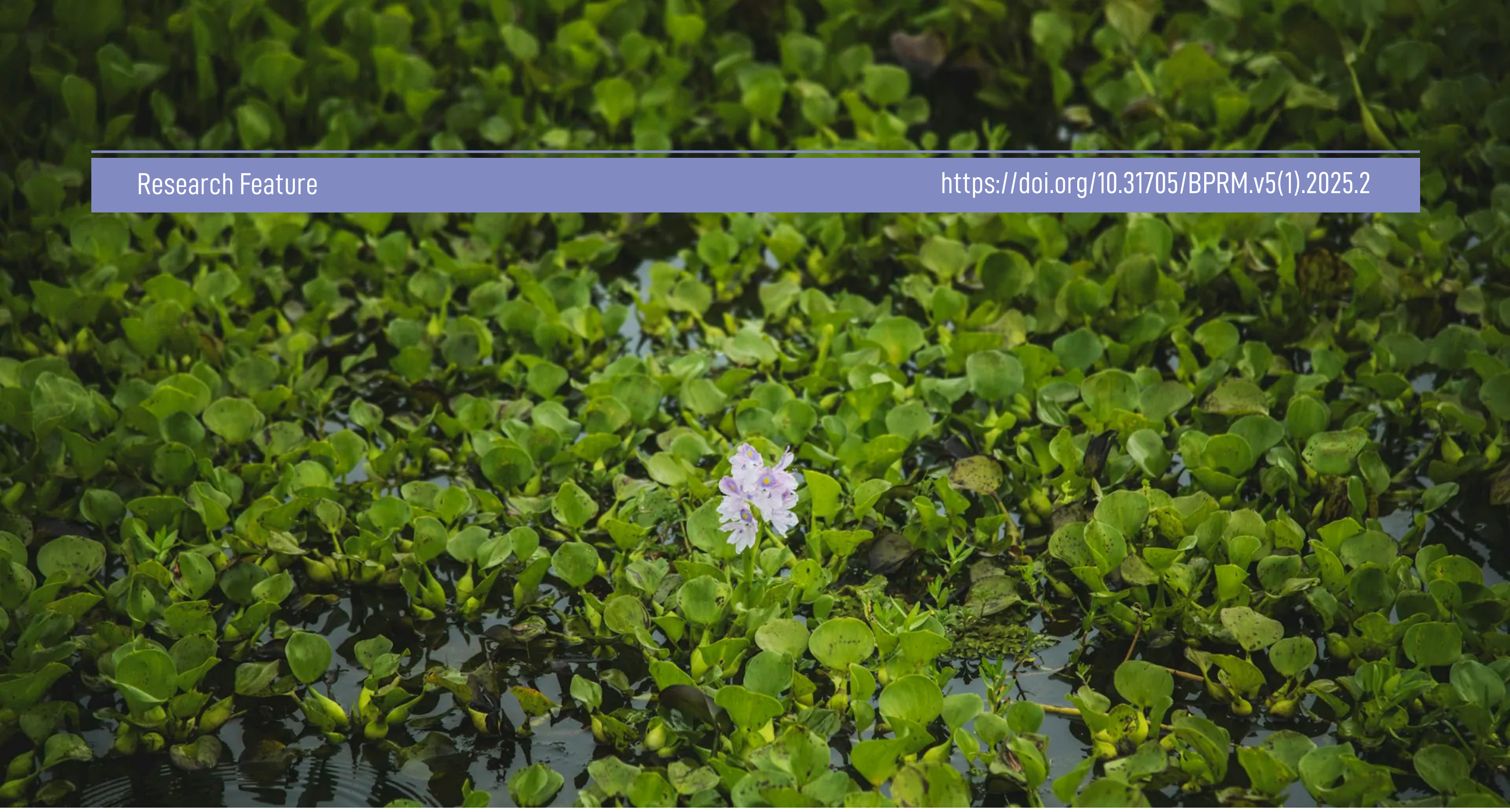

Life cycle assessment for scaled-up production of value-added products from bio-residues

"Life Cycle Assessment (LCA) is a widely recognized approach used to systematically evaluate the environmental impacts associated with all stages of a product's life cycle from the extraction of raw materials through manufacturing, distribution, usage, and final disposal. Our recent research initiatives focusing on the application of LCA for the scaled-up valorization of various bio-residues has resulted in several internationally published studies, showcasing the environmental feasibility and optimization potential of converting many bio-residues into value-added products."

Background of research

Life Cycle Assessment (LCA) is a widely recognized approach used to systematically evaluate the environmental impacts associated with all stages of a product's life cycle from the extraction of raw materials through manufacturing, distribution, usage, and final disposal. Our recent research initiatives focusing on the application of LCA for the scaled-up valorization of various bio-residues has resulted in several internationally published studies, showcasing the environmental feasibility and optimization potential of converting many bio-residues into value-added products. Bio-residues available in Sri Lanka with substantial annual quantities were selected, including approximately 1.5 – 2.0 million tonnes of rice straw, millions of tonnes of water hyacinth biomass from inland water bodies, over 100,000 tonnes of cane molasses from sugar industries, and around 300,000 tonnes of coir dust from coconut processing, all of which present significant opportunities for conversion into value-added products such as bioethanol, biopolymers, biohydrogen, and adsorbents.

Life Cycle Assessment Methodology

The standard LCA methodology follows ISO 14040/44 framework with steps such as 1. Goal and scope definition, 2. Inventory analysis, 3. Impact assessment, and 4. Interpretation of results. For a plastic product, it involves a systematic process to evaluate its environmental impacts that begins with defining the goal and scope, establishing the purpose, system boundaries with functional unit, and impact categories. The inventory phase of LCA involves gathering detailed data on material and energy inputs and outputs across each life cycle stage, including sourcing, production, transport, usage, and disposal.

In the subsequent impact assessment phase, these data are mapped to environmental categories such as climate change potential, acidification, eutrophication, toxicity, and resource depletion. The interpretation of results phase follows, analysing the results to identify source of impacts (hotspots), conduct sensitivity and uncertainty analyses, and suggest improvements. Optionally, an improvement assessment can identify opportunities to reduce environmental

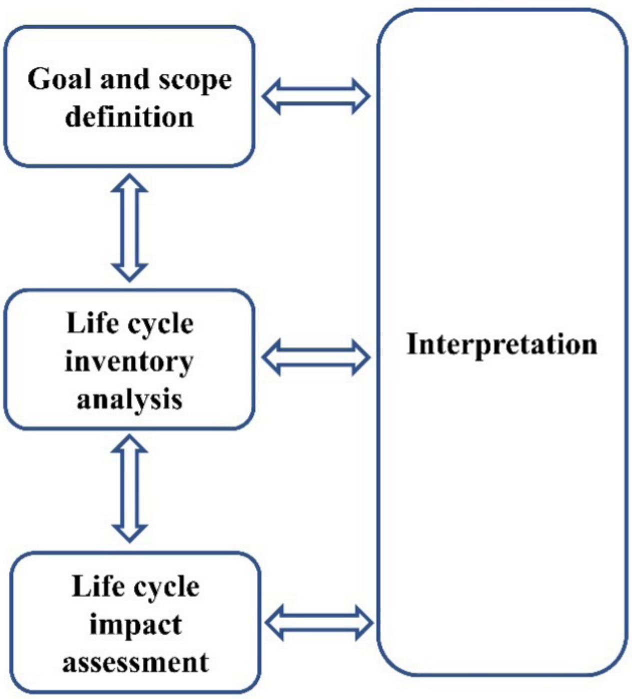

Figure 1: Standard ISO 14040/44 framework-based methodology for life cycle assessment

impacts through material substitution, process optimization, and better end-of-life management.

Life Cycle Insights into Scaled-Up Bio-Residue Valorization

Rice straw and other bio-residues, such as water hyacinth, coconut coir, sugarcane molasses, etc. have great potentials of converting into value-added products like bioethanol, biopolymers, biohydrogen, and adsorbents [1]. The existing studies had reported their laboratory-scale production, nevertheless scaled-up production and their environmental sustainability have not been comprehensively interpreted. Hence, these LCA studies focused on predicting scaled-up production of valorization options of rice straw and other selected bio-residues. Thus, several Life Cycle Assessment (LCA) studies were performed for comprehensive evaluation of their environmental sustainability [1-3]. Comparison of scaled-up processing routes, evaluation of key mass and energy flow indicators, assessment of life cycle environmental impacts, and results interpretation through multi-criteria analyses for bioethanol production and other waste valorization processes are the key objectives and highlights [1, 2]. To evaluate scaled-up production scenarios, process models were developed using Aspen Plus, while environmental assessments were conducted using SimaPro in accordance with ISO 14040 and 14044 standards. Scaled-up processing routes were developed using the Aspen Plus process simulation software and LCA was performed using the SimaPro LCA software adopting the ISO 14040-44 standard LCA methodology. The simulated mass and energy flows closely align with data from operational facilities reported in literature, supporting the validity of the modeling approach used in this research [1].

The study by Jayasundara et al. (2022) applied integrated process simulation and LCA to examine the energy efficiency and greenhouse gas emissions of producing fuel-grade bioethanol from rice straw, identifying critical points of environmental impact and energy consumption [1]. Abeysuriya et al. (2023) extended this approach to water hyacinth, an invasive aquatic plant, using scenario-based LCA to evaluate the sustainability of scaled-up bioethanol production and its potential for mitigating ecological damage [2]. Further applications were extended in the bioplastics sector by performing a comparative LCA of polylactic acid (PLA) pellet production from corn and sugarcane molasses, offering insights into feedstock selection and process efficiency for sustainable polymer manufacturing [3]. Additionally, experimental investigations were combined with LCA to assess the environmental performance of raw coir dust and processed coir pith used in heavy metal adsorption applications [4]. These studies collectively demonstrate how LCA supports informed decision-making for manufacturers and policymakers, supporting the principles of a circular economy, especially in transforming bio-residues into sustainable, value-added products.

Bioethanol derived from rice straw demonstrated favorable sustainability metrics, including a net energy ratio of 1.20, a renewability factor of 5.49, and a global warming potential of 584.8 kg CO_2 equivalent per cubic meter of bioethanol [1]. Results in further published works under this research project were evident to show water hyacinth as a feedstock for scaled-up bioethanol production [2], life cycle benefits of cane molasses as a source for scaled-up biopolymer production [3], life cycle feasibility of biopolymer production from waste cane molasses, and performance of coir as a heavy metal adsorbent [4]. This versatility contributed to many important findings and meaningful outputs from this research project.

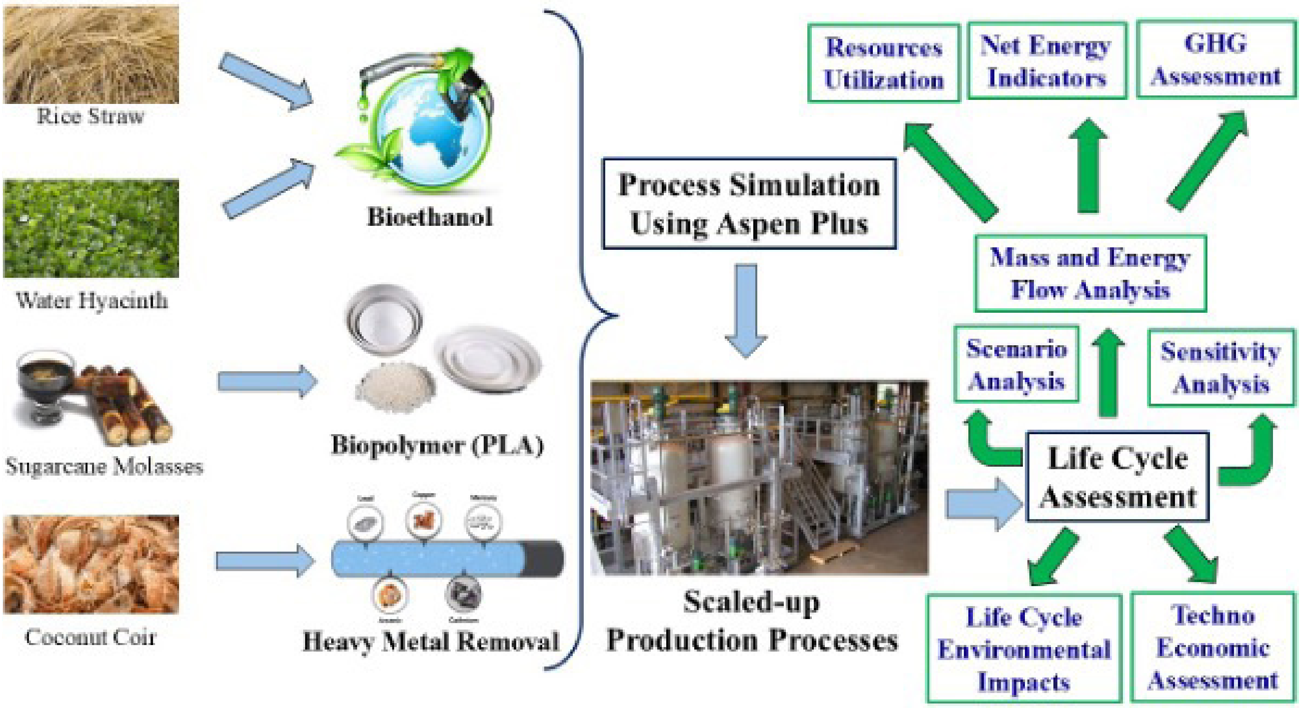

Figure 2: Summary of process simulation-based LCA adopted for multiple bio-residues

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