

Project title: Developing a Multicriteria Feasibility Assessment Model for Hemp-based Biocomposite Supply Chains Including Sociotechnical and Environmental Factors: A Case Study in Western Canada

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Introduction & Background:

Plastics, primarily derived from petrochemical sources, have seen rapid growth in production since the 1940s, with projections showing continued increase through 2050. However, their high environmental footprint, especially in terms of greenhouse gas emissions and non-biodegradable waste, poses a serious climate challenge [1]. In response, natural fibers, particularly industrial hemp, have gained attention as sustainable alternatives in biocomposite manufacturing. Hemp offers numerous benefits: eco-friendly cultivation, low water use, high tensile strength, and broad industrial applicability [2]. Despite these advantages, its integration in commercial-scale biocomposite production remains limited [3]. To overcome this challenge, however, having a proper Supply Chain (SC) management becomes pivotal. The economic and environmental performance of the SC depends heavily on processing methods and equipment selection, which vary by material. In biocomposite production, biomass typically requires several pre-processing steps to align with conversion and feedstock needs. A key step is mechanical pre-processing, particularly size reduction, to ensure particle sizes suit the final application. In this regard, the objective of this project was to develop a comprehensive Multi-Criteria Decision-Making framework based on the Analytic Network Process (ANP), which can support the sustainable pre-processing decision-makings within hemp-based biocomposites SCs, incorporating techno-economic, environmental, and social (job opportunity) measures. The chosen case study for the thesis is based on a bioproduct manufacturing company in Canada, aiming to produce hemp-based biocomposites pellets.

Relevance to Circular Economy:

This research, based on a case study in Saskatoon, supports the development of circular SCs by identifying sustainable SC pathways for converting hemp biomass into biocomposites. It evaluates the financial, environmental, and operational performance of various pre-processing equipment within its SC. The framework is scalable and can guide regional industries and policymakers in adopting cost-effective, low-impact solutions that advance the circular bioeconomy across broader agricultural and manufacturing sectors.

Methodology:

The biocomposite SC (Figure 1) begins with regional hemp sourcing and ends with the production of bioplastic pellet. In this study, The model four SC alternatives, based on combinations of biomass collection and processing equipment. These alternatives vary by baler type (round or square) and hammer mill screen size (full-screen or half-screen), which influence energy use, equipment cost, and productivity. The resulting configurations including Alternative A (Full-Round), B (Full-Square), C (Half-Round), and D (Half-Square), allow for a comparative analysis of operational efficiency and overall SC costs. The comprehensive methodology is divided into three main phases. In Phase I, a Techno-Economic Analysis is conducted using an Excel-based spreadsheet model to evaluate financial performance indicators such as Net Present Value (NPV), Payback Period, and Annual Return on Investment (ROI). This financial model incorporates both deterministic and stochastic approaches, with Monte Carlo simulation used to assess uncertainty in variables like selling price, demand, and operational costs. In Phase II, the Environmental Assessment is performed using the SimaPro software, a widely recognized tool for Life Cycle Assessment (LCA). This phase involves defining the system boundaries, conducting inventory and impact analyses, and interpreting the results, along with performing sensitivity analysis and evaluating data quality uncertainty to improve the robustness of the assessment. Phase III focuses on Sustainability Assessment through a Multi-Criteria Decision-Making (MCDM) model. It collects both qualitative and quantitative criteria and applies the Analytic Network Process (ANP) to rank alternative production scenarios, followed by sensitivity analysis to validate decision outcomes.

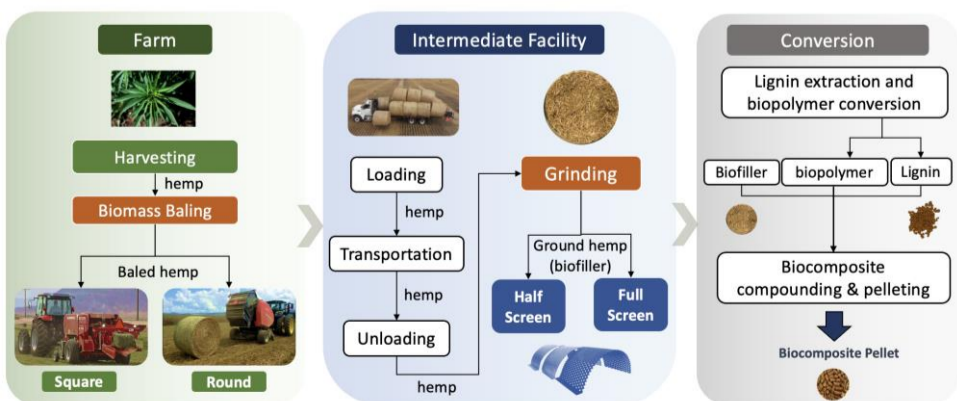


Figure 1: The SC activities and different alternatives considered in the current study.

Results & Discussion:

Focusing on economic aspect, the full-screen hammer mill with square baler achieved the highest NPV under risk (Conditional Value-at-Risk (CVaR)) and lowest price range, making it the top option for risk-averse decision-makers, while the half-screen hammer mill with round baler yielded the highest average NPV, highlighting a trade-off between risk and return. Sensitivity analysis confirmed that a 20% change in product selling price leads to a 72% change in NPV, identifying it as the most influential variable. As shown in the Figure 2(a) with the example of one configuration (SC2 or alternative B), a mean NPV of \$53.96 million, a VaR of \$2 million, and a CVaR of -\$9.73 million are obtained, reflecting the risk of substantial losses in the worst 5% of scenarios. These findings underscore the necessity of incorporating advanced risk metrics, such as VaR and CVaR, when evaluating SC investments under uncertainty. From the environmental impact perspective, the Half-Round option (half-screen hammer mill & round baler) exhibited 30%–44% higher environmental impacts due to increased biomass harvested and 9% more diesel usage, despite offering better product quality. As shown in Figure 2(b), the Half-Round setup showed significantly greater impacts in Carcinogenics, Ecotoxicity, and Non-Carcinogenics categories ($p < 0.01$), compared to the Full-Square configuration, which emerged as the more environmentally favorable alternative. Also, focusing on bottlenecks, mitigation strategies such as nitrogen-reduced fertilizer use could reduce environmental impacts significantly. Incorporating additional factors of social and technical ones, the final decision making is shown in Figure 3 (a). According to Figure 3(b), alternative B (Full-Square) ranks highest under economic focus, while Alternative A (Full-Round) is preferred for environmental sustainability. When social and technical factors are prioritized, Alternative C (Half-Round) consistently (60% of cases) performs well, demonstrating strong reliability and labor impact.

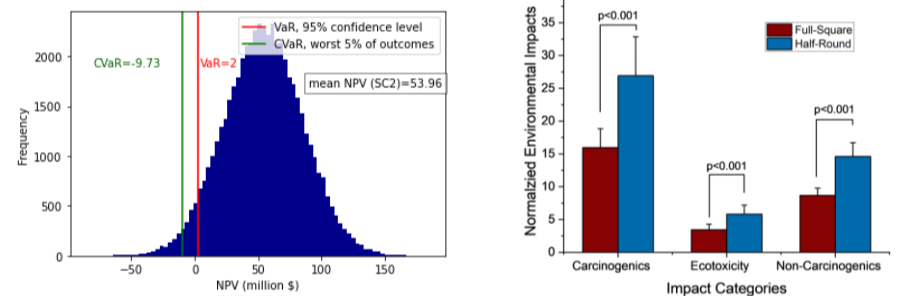


Figure 2: (left: a) Probability of NPV of Alternative B. (right: b) Characterized Life Cycle Impact Assessment (LCIA) results and uncertainty analysis.

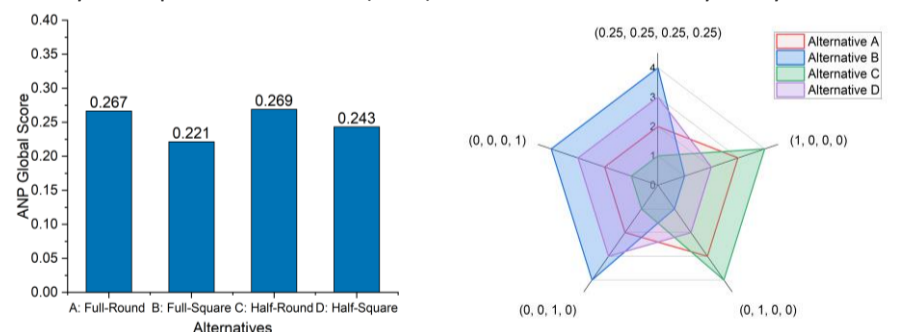


Figure 3: (left: a) Ranking of the SC configurations. (right: b) Sensitivity analysis of cluster importance.

Conclusion & Next Steps:

In this work, a novel decision-making framework for sustainable hemp-based biocomposite production is developed, focusing on four biomass pre-processing configurations in Saskatchewan. Future work will focus on developing an interactive analysis tool to support users in visualizing trade-offs across economic, environmental, and social criteria. Additionally, the team is working on marketing and pricing strategies to support commercialization, including defining price ranges for biocomposite pellets and identifying target markets such as 3D printing and automotive applications.

References:

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2. P. J. Herrera-Franco and A. Valadez-González, "Mechanical properties of continuous natural fibre-reinforced polymer composites," *Compos Part A Appl Sci Manuf*, vol. 35, no. 3, pp. 339–345, Mar. 2004, doi: 10.1016/j.compositesa.2003.09.012.
3. J. Cherney, and E. Small, "Industrial Hemp in North America: Production, Politics and Potential," *Agronomy*, vol. 6, no. 4, p. 58, Nov. 2016, doi: 10.3390/agronomy6040058.

Further reading:

Akbarian-Saravi, N., Sowlati, T., & Milani, A. S. (2024). Analytic Network Process for Multicriteria Decision-Making in Sustainable Composites Supply Chain Management. In *IISE Annual Conference. Proceedings* (pp. 1-6). DOI:10.21872/2024IISE_6101.

Akbariansaravi, N. (2025). A sustainability assessment model for selecting pre-processing equipment in hemp-based biocomposite supply chains under techno-economic, environmental, and social measures (Doctoral dissertation, University of British Columbia).