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Towards an Integrated Life Cycle Sustainability Assessment Framework for Small-Scale Alpine Biorefineries Based on Agricultural Side Streams

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Abstract

Small-scale and decentralised biorefinery concepts may contribute to a more circular use of agricultural side streams in Alpine regions. By converting locally available residues into bio-based products, they may reduce resource losses, substitute conventional inputs and strengthen regional farm-to-fork value chains. However, sustainability assessments of such systems often remain fragmented. Life Cycle Assessment studies usually focus on environmental impacts, while economic aspects, such as Life Cycle Costing, and social aspects, such as Social Life Cycle Assessment, are addressed separately or only partially (Lin et al., 2020; Solarte-Toro et al., 2023). This limits comparability between valorisation pathways and reduces the usefulness of assessments for regional decision-making. This contribution proposes the adaptation of an existing integrated Life Cycle Sustainability Assessment framework to the specific context of small-scale Alpine biorefineries. The objective is not to develop a new assessment concept from scratch, but to operationalise a comprehensive framework for regionally embedded agricultural side-stream valorisation systems. Building on the framework by Hackenhaar et al. (2024), a literature review was conducted covering the period from May 2021 to May 2026. The search combined the keywords “Life Cycle Sustainability Assessment”, “LCSA”, “biorefinery”, “agricultural side streams”, “food side streams”, “bioeconomy” and “Alpine agriculture”. Titles, abstracts and keywords were screened to identify relevant studies and derive indicators suitable for small-scale, decentralised biorefinery applications. Additionally, a focus group discussion with eleven stakeholders from the Austrian Alpine region, including representatives from farming, policy, educational institutions, waste and environmental consulting, and non-profit organizations, was conducted in March 2026 to identify the opportunities and limitations of biorefineries in Alpine regions, as well as relevant indicators. The focus group discussion was recorded, transcribed, and subsequently analyzed to systematically capture stakeholder perspectives and integrate them into the adapted framework. The adapted framework is designed for small-scale, decentralised applications in Alpine regions, where empirical data are limited. Potential valorisation pathways may include fertilising and mulching inputs, nutrient recovery products, bio-based materials such as dyeing components, and functional extracts. The environmental dimension builds on Life Cycle Assessment indicators such as climate change, resource use, nutrient recovery and substitution of conventional inputs. The economic dimension considers investment and operating costs, transport requirements, product value and regional value creation. The social dimension addresses stakeholder groups relevant to Alpine systems, including farmers, processors, local communities and consumers.

Keywords: Life Cycle Sustainability Assessment, Alpine biorefineries, agricultural side streams, circular bioeconomy, regional value chains

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