ASSESSMENT OF THE TECHNOLOGICAL FEASIBILITY AND ECONOMIC VIABILITY OF RESIDUE VALORISATION IN APPLE PROCESSING

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Apple pomace, a major by-product of the apple processing industry, was assessed through two alternative valorisation pathways business models: pectin extraction for premium gelling sugar incorporation and fruit leather production. Both models were developed on pilot-scale based data and assessed through discounted cash flow analysis. Clustered pectin extraction (30 t/year capacity) demonstrates strong profitability (Net Present Value > €240,000, Internal Rate of Return > 100%). In contrast, single-farm scale processing and fruit leather production (6.6 t/year capacity) were economically viable only for/when targeting premium market segments. The integration of additional residue valorisation options, such as specialty paper production or ethanol regeneration, improved the overall sustainability and resource efficiency further. The findings confirm that small-scale circular approaches can drive economic resilience when focusing on high-value markets and employing systemic, resource-efficient design.

Keywords:
apple pomace, pectin, paper, fruit leather, economic evaluation of the prototype, biomass residues, biomass side streams, biomass valorisation, sustainable business model

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1 Introduction

Apple pomace is produced globally at a rate of 4 million tonnes per annum, and is as such one of the most significant types of agri-food residues and waste (Kauser, 2024; Gołębiewska, 2022). Apples are by far the most important fruit species in the Slovenian agricultural output (about 50,000 tonnes yearly), which is used mainly for food as fresh fruit, and in the form of apple products such as apple juice, apple cider vinegar, dried apples, etc. Apple processing generates large amounts of apple pomace (estimated at about 1,200 tonnes of dry matter), which are usually processed into animal feed or compost. Apple pomace contains various high-value components, such as phenolic compounds (e.g. flavonoids, hydroxycinnamic acids or dihydrochalcones), dietary fibre and high pectin contents (Bhushan, 2008; Barreira, 2019). Most commonly, apple pomace contains abundant pectin and cellulose, between 9 and 20 % pectin and between 7 and 44 % cellulose, making apple pomace a potential source of pectin and cellulose (Costa, 2022; Ma, 2019).

The material flow balance conducted within the project "Circular technological concepts and business models in Slovenian agriculture (V4-2208; Juvančič, 2025)" confirmed the potential of apple pomace as a raw material source for further valorisation through cascading use. Two prototype systems were developed to assess the economic potential of apple pomace valorisation in Slovenia. The first prototype explored pectin extraction, with an option for the remaining extraction residue to be used subsequently to produce speciality papers. The second prototype focused on the production of fruit leather as a plant-based alternative to conventional animal leather.

The cascading valorisation of apple pomace has emerged as a showcase for farm-level circularity, lowering disposal costs and opening new revenue streams simultaneously. The technological prototypes have subsequently been translated into circular and sustainable business models that are transferable to the context of professional fruit-growing farms, or micro-enterprises engaging in these activities. Both concepts – pectin extraction and fruit leather production, intentionally target higher-end market segments, where eco-design and local provenance add differentiating value able to offset the limited raw-material base and higher unit cost typical of family farms (Juvančič, 2025).

2 Methods

In this article we focus on the process of transforming technological prototypes of agricultural by-product utilisation into functioning business models. In doing so, we follow the principle that business models can be used as supplementary activities on farms or small-scale processing plants in rural areas. In cooperation with the developers of the technological prototypes, we have translated the proposed technological solutions into a business model that describes the organisation of the business process, the technological parameters of production and the form of the economic entity. The scope of apple pomace utilisation was defined based on the inventory of production mass flows on Kastelic farm, which participated in the project. The analytical framework mirrors the stepwise approach described by Fatur et al. (Fatur, 2025), in which the prototype mass balances are first translated into cost items, and thereafter into discounted-cash-flow indicators:

- Technological prototype 1: Extraction of pectin, sales of pectinated sugar: For pectin extraction two capacity scenarios were evaluated 6.6 tonnes annually (single farm) versus 30 tonnes (cluster of farms).
- Technological prototype 2: Production of fruit leather: 6.6 tonnes of apple pomace per year were evaluated for fruit leather production.

The economic viability is gauged over ten years at a real 6 % discount rate, using straight-line depreciation for the resulting Net Present Value (NPV) and Internal Rate of Return (IRR). A qualitative discussion of the loop-closing options – either outsourcing the cellulose-rich residue to a niche paper mill, or fermenting it to regenerate extraction ethanol – followed the sustainability reasoning advanced in the second stage of the cascade.

3 Results

Two technological prototypes, with their technical specification, were developed for valorisation of the technological feasibility and economic viability of apple processing residue. Figure 1. represents the technical scheme of pectin extraction, used for the description of the technological prototype 1. This scheme was developed based on known experimental results from the literature, and was used for following economic evaluations.

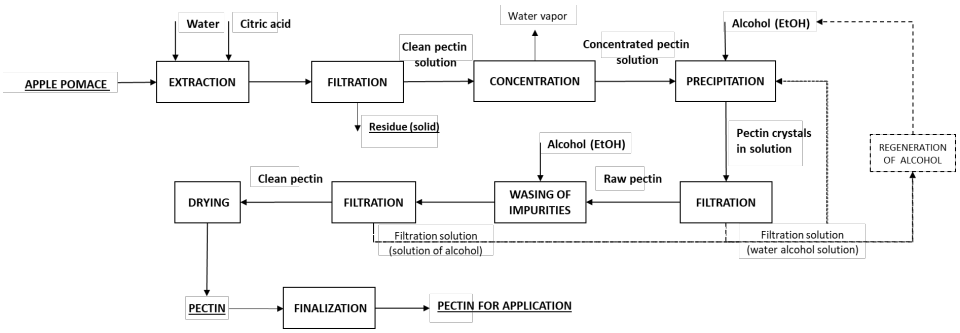

Figure 1: The technical scheme for the extraction of pectin (technological prototype 1).
Source: own, author: Katja Makovšek

Figure 2 represents the scheme for the second evaluated technological prototype, the production of fruit leather. The prototype was developed based on the previous projects.

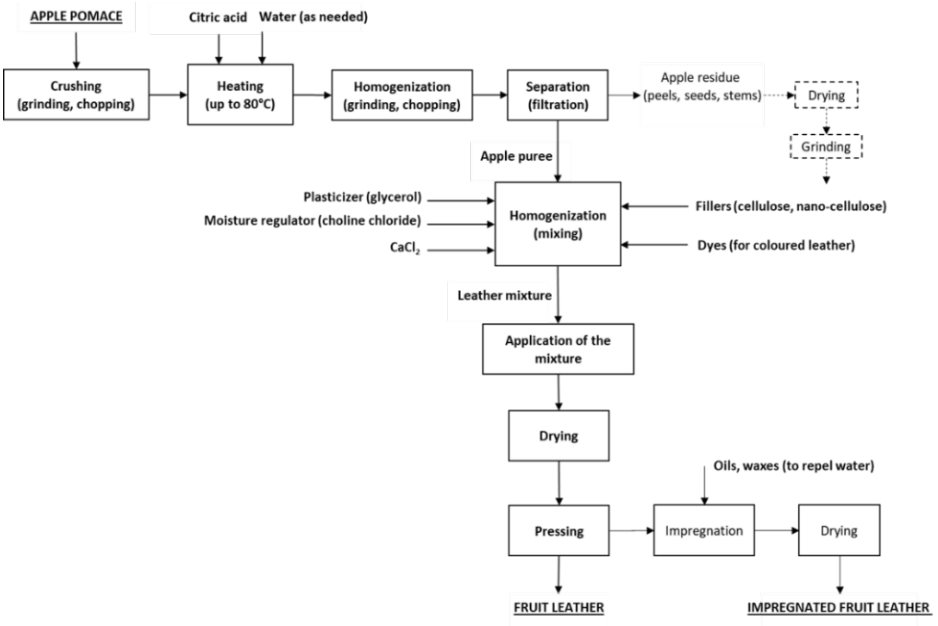

Figure 2: Prototype 1: Production of fruit leather (technological prototype 2).
Source: Fatur, 2025, author: Katja Makovšek

At the cluster farm scale (30 t annually), pectin extraction converts pomace into about 720 kg of high-methoxyl pectin, subsequently blended into 9,650 kg of premium gelling sugar. With a farm-gate price of 22.4 €/kg, the annual revenue reaches 216,000 €, while the variable costs are dominated by the ethanol purchases (≈ 109,000 €). A modest equipment set – an extractor, jacketed tanks and filtration – requires 19,500 €, complemented by a 15,500 € modular hall. Under these premises the own cost for pectin settles at 3.86 €/kg, the NPV attains 240,192 €, at the IRR 101 %, confirming strong viability when the raw material is pooled among several farms. Scaling the same technology down to 6.6 tonnes annually lifts the unit cost to 5.10 €/kg; the NPV shrinks to 17,695 € and the IRR to 15 %, making the profitability contingent on sustained premium pricing, as already noted for the pectinated sugar marketed through direct sales.

Table 1: Cash flow on two cases of production scale for pectin extraction on a farm level.

Farm scale	Cluster of farms 30 t/y	Small farm 6 t/y
Total Revenue (TR)	216,000 €	47,520 €
Total Costs (TC)	189,480 €	45,657 €
Differential cash flow	34,829 €	6,618 €
IRR	101%	15%
NPV	240,192 €	17,695 €

The fruit leather, produced from 6.6 tonnes of pomace blended with natural binders, yields roughly 1,200 kg of dehydrated fruit leather sheets. If priced at 60 €/kg in the eco-packaging niches the concept will generate 72,000 € annually against an own cost of 36.8 €/kg. With total costs amounting to 48,747 €, the NPV reaches 171,655 € and the IRR approaches 86 %. The result aligns with the general finding that high-margin, design-driven outlets are indispensable for small-scale circular ventures.

Table 2: Cash flow of apple leather production on a farm level.

Fruit leather	Production scale 6.6 t/y
Total Revenue (TR)	72,000 €
Total Costs (TC)	48,747 €
Differential cash flow	23,253 €
IRR	86%
NPV	171,655 €

The residual press-cake can either feed a niche paper line – incurring 1.20 €/kg of service cost as reported for specialty sheets – or undergo fermentation and distillation, recovering up to 60 % of the ethanol input and lowering the variable expenses further.

4 Conclusion

The study confirms that economic resilience hinges on premium positioning. Clustered pectin extraction leverages economies of scale to deliver an IRR above 100 %, whereas single-farm installations remain borderline profitable unless backed by strong branding. Fruit leather, though more speculative technologically, achieves attractive returns owing to favourable price–cost differentials and modest capital needs. In both cases, loop-closing options – be it cellulose-based paper for promotional use or in-house ethanol regeneration – enhance the circular performance and reinforce the storytelling potential that underpins market acceptance. The evidence thus supports the broader claim that circular products from agri-food by-products can succeed commercially when embedded in well-crafted, sustainability-oriented business narratives.

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