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Integrated techno-economic and screening life-cycle assessment of a decentralized onion peel biorefinery for sequential recovery of anthocyanin- and quercetin-rich fractions

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Abstract

Onion peel is a concentrated source of anthocyanins and quercetin, but industrial translation requires process configurations that connect experimentally demonstrated extraction performance with scale-up economics and environmental resource demand. This study developed an experimentally anchored, decentralized onion-peel biorefinery using a 1,000 kg day^{-1} base-case throughput operated for 300 days $year^{-1}$. Three configurations were compared: anthocyanin-rich powder only (Scenario 1), quercetin-rich powder only (Scenario 2), and sequential co-recovery of anthocyanin- and quercetin-rich fractions (Scenario 3). Anthocyanins were recovered by mild acidified-water extraction at pH 3.0 and 50°C for 60 min, whereas quercetin recovery used 50% aqueous ethanol with sequential hemicellulase/cellulase treatment and downstream clarification. Process measurements showed 96% anthocyanin extraction-medium recovery in Scenarios 1 and 3, while quercetin-solvent recovery was 93% in Scenario 2 (46% ethanol in the recovered solvent versus 50% in the fresh solvent) and 96% in Scenario 3 (47% versus 50%). Direct fixed capital requirements were approximately INR 13 crore for the single-product configurations and INR 20 crore for the integrated configuration. At base throughput, annual operating costs were approximately INR 0.703, 7.010, and 7.32 crore, while annual revenues were approximately INR 3.005, 9.725, and 12.725 crore for Scenarios 1–3, respectively. Base-case net present value (NPV) was INR 0.18, 2.64, and 11.15 crore, with corresponding internal rate of return (IRR) values of 10.64%, 13.75%, and 19.25%; increasing throughput to 1,500 kg day^{-1} raised IRR to 18.59%, 22.78%, and 30.35%. A screening gate-to-gate environmental assessment based on the documented utility inventory indicated electricity demand of 40–120 kWh and steam demand of 1.08–1.35 t per tonne of onion peel processed, corresponding to a utility-related CO_2 proxy of approximately 224–330 kg CO_2 t^{-1} feed. Scenario 3 had the highest absolute utility demand, but it delivered the strongest economic performance and the most complete recovery of value from the same biomass. The integrated configuration is therefore identified as the preferred development pathway, with future commercial translation centered on sustaining the measured solvent-recovery performance, controlling recycled ethanol strength, product qualification, heat integration, low-carbon utilities, and sustained plant utilization.

Highlights

An experimentally anchored 1,000 kg day decentralized onion-peel biorefinery was assessed under three product configurations.

Sequential anthocyanin + quercetin recovery achieved the strongest base-case economics (NPV INR 11.15 crore; IRR 19.25%).

Increasing throughput to 1,500 kg day raised the integrated-process IRR to 30.35%.

Screening utility-related CO burden was 224–330 kg CO per tonne of onion peel processed.

Extraction-medium/solvent recovery was 96% in Scenario 1, 93% in Scenario 2, and 96% for both extraction stages in Scenario 3; recovered quercetin solvent contained 46–47% ethanol versus 50% in the fresh solvent.

1. Introduction

The transition from linear resource use to circular processing has increased interest in biorefineries that convert agricultural and food-processing residues into functional ingredients, chemicals, fuels and energy. In food systems, this opportunity is particularly relevant because many residues are generated in geographically concentrated processing chains and already possess high concentrations of structurally diverse compounds that are expensive to synthesize or isolate from conventional raw materials. Onion peel is one such residue. Although it represents only a small fraction of bulb mass, it is enriched in flavonoids, particularly quercetin and its glycosides, red-purple anthocyanins, other phenolics and structural polysaccharides. Recent reviews and experimental studies have therefore shifted the view of onion peel from a disposal problem to a potentially valuable feedstock for food, nutraceutical, and biomaterial applications (Sagar & Pareek, 2020; Stoica et al., 2023; Bains et al., 2023; Samota et al., 2022; Joković et al., 2024).

The key challenge is no longer demonstrating that onion peel contains valuable compounds, but designing a process that recovers them at sufficient yield and quality while maintaining economic viability and avoiding a shift of burden toward solvent, chemical and energy consumption. Published onion-waste studies have demonstrated quercetin recovery using solvent, ultrasound, microwave and enzyme-assisted approaches, while anthocyanin recovery is favored by mild acidic conditions that protect the flavylium form (Abd-ElSalam et al., 2021; Jang et al., 2013; Choi et al., 2015; Benito-Román et al., 2020; Tena & Asuero, 2022). Most studies, however, remain laboratory-scale and focus on a single target compound. Consequently, they provide limited evidence on whether the added capital and operating complexity of a cascade biorefinery is justified by incremental revenue, greater feedstock utilization and reduced dependence on a single product market.

A second unresolved gap is that economic and environmental assessments are frequently conducted independently. For emerging biorefineries, this separation can favor designs that appear profitable but depend strongly on high product selling prices or intensive utilities, or designs that reduce residual waste but are economically unattractive at realistic throughput. Coupling techno-economic analysis (TEA) with environmental assessment is therefore increasingly important for early-stage biorefinery decision-making (Pérez-Almada et al., 2023). For agro-residue systems, feedstock logistics and decentralized siting are equally important because transport distance can erode both economic and environmental advantages (Cho et al., 2025).

India is a particularly relevant case because onion production and processing are concentrated in major producing regions (Agricultural and Processed Food Products Export Development Authority, n.d.), while onion peel is commonly directed to mixed organic waste or low-value uses. A decentralized process

located near onion-processing clusters can reduce long-distance feedstock transport and enable residue-specific valorization. The present study addresses the laboratory-to-process-design translation gap through a common-basis comparison of three product portfolios at a base scale of 1,000 kg onion peel day^{-1}. Its novelty lies in directly linking experimentally established anthocyanin and quercetin recovery conditions with process-scale capital and operating requirements, profitability sensitivity and a gate-to-gate environmental hotspot screen. The central scientific question was whether sequential co-recovery can generate sufficient additional value to justify the added equipment and utility demand relative to single-product extraction. The objectives were to (i) define scalable process configurations from experimentally established extraction conditions; (ii) estimate capital investment, operating cost, revenue, net present value (NPV), and internal rate of return (IRR); (iii) quantify sensitivity to plant capacity, selling price and production cost; and (iv) integrate a screening gate-to-gate life-cycle assessment using the documented material and utility inventory to identify eco-economic scale-up priorities.

2. Materials and methods

2.1 Process-design basis and scale

The process design was developed from laboratory optimization, pilot-scale handling experience, equipment information and engineering scale-up assumptions generated within the broader onion-peel valorization work. This experimentally anchored basis was used to retain realistic extraction conditions, practical product yields and process sequencing while translating the system to a decentralized commercial-scale design. A decentralized biorefinery was selected as the reference configuration because onion processing is geographically clustered and because limiting the feedstock catchment can reduce logistics cost and emissions. The base case processes 1,000 kg onion peel day^{-1} (125 kg h^{-1} over an 8 h operating shift) for 300 operating days $year^{-1}$. A nominal feedstock collection radius of approximately 50 km was considered consistent with the logistics range commonly used for decentralized agricultural-residue systems (Cho et al., 2025; Purohit & Dhar, 2015).

2.2 Scenario definition

Three configurations were evaluated. Scenario 1 recovers an anthocyanin-rich powder using acidified water and sends the solid fraction to residual biomass use. Scenario 2 recovers a quercetin-rich powder using aqueous ethanol and enzyme-assisted extraction. Scenario 3 integrates the two operations sequentially, recovering anthocyanins first and quercetin from the remaining solids, after which the residual pectic/cellulosic fraction is available for further valorization or soil-oriented use. The integrated configuration therefore represents a cascade rather than independent parallel extraction. The configuration assumptions are summarized in Table 1, and the process sequence is illustrated in Fig. 1.

Table 1
Process configurations, product assumptions and measured extraction-medium/solvent recovery.

Parameter	Scenario 1	Scenario 2	Scenario 3
Primary products	Anthocyanin-rich powder	Quercetin-rich powder	Anthocyanin- + quercetin-rich powders
Anthocyanin extraction	pH 3.0; 50°C; 60 min	—	pH 3.0; 50°C; 60 min
Quercetin extraction	—	50% ethanol; 1:20 (w/v); enzymes	50% ethanol; 1:20 (w/v); enzymes
Anthocyanin-rich powder yield	2.0% of feed	—	2.0% of feed
Quercetin-rich powder yield	—	7.2% of feed	7.2% of feed
Assumed anthocyanin purity	40%	—	40%
Assumed quercetin purity	—	50%	50%
Residue route	Residual biomass use	Residual biomass use	Pectic/cellulosic fraction for further valorization
Extraction-medium/solvent recovery	Anthocyanin: 96%	Quercetin: 93%	Anthocyanin: 96%; Quercetin: 96%
Recovered ethanol concentration after quercetin extraction	—	46% (fresh solvent: 50%)	47% (fresh solvent: 50%)

2.3 Anthocyanin extraction and downstream processing

Anthocyanins were extracted using a mild hot-water process selected to balance mass transfer and pigment stability. Onion peel was contacted with acidified water (pH 3.0) at 50°C for 60 min under continuous agitation. The liquid phase was separated by filtration, clarified through sequential filtration, and concentrated before low-temperature drying under reduced pressure. The low-pH, moderate-temperature regime is consistent with anthocyanins' sensitivity to neutral/alkaline pH, oxygen, and high temperature (Samota et al., 2022; Tena & Asuero, 2022). For the TEA, the practical anthocyanin-rich powder yield was 2% of onion-peel feed, and the product was valued at INR 5,000 kg^{-1} at approximately 40% anthocyanin purity. Measured extraction-medium recovery after anthocyanin processing was 96% in Scenario 1. The first stage of anthocyanin extraction in Scenario 3 also showed 96% recovery.

2.4 Quercetin extraction and downstream processing

Quercetin recovery used 50% ethanol-water at a solid-to-solvent ratio of 1:20 (w/v), with continuous mixing at 500 rpm. In the enzyme-assisted route, the slurry was first adjusted to pH 4.5 and treated with hemicellulase at 40°C for 2 h, then adjusted to pH 8.0 and treated with cellulase at 60°C for an additional 2 h. The sequential treatment disrupts hemicellulosic and cellulosic structures and improves release of

cell-wall-associated flavonoids. After extraction, solids were removed by filtration and the quercetin-rich liquid was clarified, concentrated and vacuum-dried. The process is consistent with prior evidence that combined physical and enzyme-assisted treatments can intensify quercetin recovery from onion waste (Abd-ElSalam et al., 2021; Jang et al., 2013; Sahu et al., 2025). The scale-up model used a practical quercetin-rich powder yield of 7.2%, 50% quercetin purity and a selling price of INR 4,500 kg^{-1}. Solvent recovery and recovered-solvent ethanol concentration were treated as separate process-performance measurements. In Scenario 2, 93% of the quercetin extraction solvent was recovered, and the recovered solvent contained 46% ethanol compared with 50% in the original extraction solvent. In Scenario 3, quercetin-solvent recovery increased to 96%, and the recovered solvent contained 47% ethanol compared with the original 50% ethanol solution. Detailed solvent-circulation, measured bulk-recovery, unrecovered-fraction, and recovered-ethanol-strength data for the corresponding extraction stages are reported in Supplementary Table S5.

2.5 Capital-cost and operating-cost estimation

Equipment purchase costs were based on installed/pilot-facility information from the experimental program and scaled to alternative capacities using the conventional power-law relation $C_2 = C_1(Q_2/Q_1)^{0.6}$, where C_1 and C_2 are equipment costs at capacities Q_1 and Q_2, respectively (Peters et al., 2003; Turton et al., 2012; Towler & Sinnott, 2021). Direct fixed capital (DFC) included direct plant costs, indirect engineering and construction costs, contractor fees, and contingency. The analysis year was 2026, and the base financial horizon was 15 years with a 10% discount rate. A 23% income-tax assumption and 300 operating days $year^{-1}$ were applied consistently across scenarios. The comparative TEA used model-derived NPV and IRR values as common decision metrics. Depreciation and salvage value were not treated as independent sensitivity variables; accordingly, the results are interpreted as a comparative feasibility and scale-selection analysis rather than a bankable project-finance appraisal. These accounting conventions can be refined during commercial due diligence to reflect the selected financing structure without altering the process-level comparison presented here. Supplementary Tables S1–S3 report the detailed direct fixed-capital build-up, base-case daily material/consumable/utility cost basis, and annual operating-cost components, respectively. The base-case techno-economic assumptions are summarized in Table 2.

Table 2
Base-case techno-economic assumptions.

Parameter	Value
Plant throughput	1,000 kg onion peel day^{-1}
Operating schedule	8 h day^{-1}; 300 days $year^{-1}$
Analysis year	2026
Project life	15 years
Discount rate	10%
Income tax	23%
Electricity price	INR 9 kWh^{-1}
Steam price	INR 1,500 t^{-1}
Cooling-water price	INR 18 t^{-1}
Onion-peel procurement/handling	INR 5,500 t^{-1}
Anthocyanin-rich powder selling price	INR 5,000 kg^{-1}
Quercetin-rich powder selling price	INR 4,500 kg^{-1}

2.6 Profitability and sensitivity analysis

Annual revenue was calculated from practical product yields and base selling prices. Profitability was evaluated using model-derived NPV and IRR values over the 15-year project horizon. One-factor sensitivity analysis varied throughput (500, 1,000 and 1,500 kg day^{-1}), operating days (270, 300 and 330 days $year^{-1}$), project life (12, 15 and 18 years), income tax (20%, 25% and 30%), unit production cost (± 20%) and product selling price (± 20%). The analysis was designed to identify whether profitability was primarily process-cost-driven, market-price-driven or scale-driven and to determine which variables should receive priority during subsequent process development. The annual feed, product-mass, residual-biomass, and revenue calculation basis used for the base case is reported in Supplementary Table S4.

2.7 Screening life-cycle assessment

The screening gate-to-gate life-cycle assessment (LCA) was intentionally designed as an early engineering decision tool to identify environmental hotspots and variables to measure during subsequent scale-up; it was not intended to substitute for a database-driven, ISO 14040/14044-compliant product LCA (International Organization for Standardization, 2006a, 2006b). The functional unit (FU) was processing 1,000 kg of onion-peel feed at the biorefinery gate. The boundary included

process electricity, generated steam, process water and cooling water. Upstream cultivation was assigned no burden because onion peel enters the system as a processing residue; capital equipment, buildings, downstream product use, avoided-disposal credits and end-of-life benefits were outside the screening boundary. Chemical and solvent flows were retained as explicit inventory/hotspot variables but were not converted to midpoint impacts because verified upstream life-cycle datasets for ethanol, enzymes, acids and bases were outside the process dataset used in this study. Measured recovery values were nevertheless used to interpret solvent-loss intensity: anthocyanin extraction-medium recovery was 96% in Scenarios 1 and 3, while quercetin-solvent recovery was 93% in Scenario 2 and 96% in Scenario 3; the recovered quercetin solvent contained 46% and 47% ethanol, respectively, versus 50% in the fresh solvent. This boundary avoids false precision at the present design stage while enabling a consistent comparison of the three configurations. The approach follows the principle of coupling TEA and environmental screening at early biorefinery design stages (Pérez-Almada et al., 2023) and is consistent with recent food-residue extraction studies that use LCA to identify energy and solvent hotspots (Duggal et al., 2024).

Electricity demand was back-calculated from the documented utility cost at INR 9 kWh^{-1}. Steam use was obtained from the specified steam cost at INR 1,500 t^{-1}, and water use from the corresponding unit prices. Electricity-related CO_2 was calculated using the 2024–25 weighted-average Indian grid emission factor of 0.710 t CO_2 MWh^{-1} reported by the Central Electricity Authority (2025). For screening combustion emissions from steam generation, we used natural gas as the reference boiler fuel and the Intergovernmental Panel on Climate Change (IPCC, 2006) default CO_2 factor of 56.1 kg CO_2 GJ^{-1}. We assumed a thermal requirement of 2.75 GJ t^{-1} steam and 85% boiler efficiency, yielding approximately 181.5 kg CO_2 t^{-1} steam. The resulting climate indicator is therefore a utility-related CO_2 proxy rather than a full cradle-to-gate carbon footprint. Supplementary Table S6 reports the factors and equations used for the screening environmental indicator.

3. Results and discussion

3.1 Process integration and product portfolio

The process comparison shows a clear trade-off between simplicity and product diversification. Scenario 1 has the mildest process, relying mainly on acidified-water extraction, filtration and drying. Scenario 2 introduces ethanol handling, sequential enzyme treatment, pH adjustment and additional downstream purification. Scenario 3 combines both trains and therefore has the highest equipment count and utility requirement, but it also captures two high-value product streams before directing the remaining structural biomass to further use. This cascade is important because a single-product route leaves economic value in the residue and can make overall feasibility dependent on one product market.

The material basis also identifies an important commercial design variable: solvent circulation. At 1:20 (w/v), 1,000 kg of peel corresponds to approximately 20,000 L of extraction medium per batch-equivalent

throughput. A 50% ethanol solution would contain approximately 10,000 L of ethanol in gross circulation. Measured recovery data confirm that this large circulating inventory is predominantly recycled rather than repurchased. Scenario 2 achieved 93% quercetin-solvent recovery, with 46% ethanol in the recovered stream compared with 50% in the fresh extraction solvent. In Scenario 3, the anthocyanin extraction medium was recovered at 96%, and the subsequent quercetin solvent was also recovered at 96%, with 47% ethanol in the recovered stream. The integrated configuration therefore shows a more favorable solvent-recycle performance than the stand-alone quercetin route. At the same time, the decrease in ethanol concentration from the original 50% demonstrates that bulk solvent recovery and solvent strength are distinct variables; the recovered stream requires controlled ethanol make-up or reconditioning before reuse. Maintaining the observed recovery while minimizing ethanol-strength drift is consequently a key scale-up performance indicator (KPI) because lower recovery would increase operating cost, fresh-solvent demand, fire-safety requirements and upstream environmental burden.

3.2 Capital investment and annual operating cost

The DFC requirement was approximately INR 13 crore for each single-product configuration and INR 20 crore for the sequential integrated configuration. The increase for Scenario 3 reflects duplicated/expanded extraction, filtration, concentration and drying requirements. Relative to Scenario 1, the larger investment in Scenario 3 is therefore a direct consequence of product diversification rather than simple scale enlargement. The base-case capital, operating-cost, revenue, NPV, and IRR results are summarized in Table 3.

Table 3
Base-case capital, operating cost and revenue by scenario.

Metric	Scenario 1	Scenario 2	Scenario 3
Direct fixed capital (INR crore)	13.0	13.0	20.0
Annual operating cost (INR crore)	0.703	7.010	7.32
Annual anthocyanin revenue (INR crore)	3.000	0	3.000
Annual quercetin revenue (INR crore)	0	9.720	9.720
Annual residue revenue (INR crore)	0.0053	0.0050	0.0049
Total annual revenue (INR crore)	3.005	9.725	12.725
Base NPV (INR crore)	0.18	2.64	11.15
Base IRR (%)	10.64	13.75	19.25

Operating costs differed much more strongly than capital costs. Scenario 1 required approximately INR 0.703 crore $year^{-1}$, while Scenarios 2 and 3 required about INR 7.01 and 7.32 crore $year^{-1}$, respectively. The large increase is driven by the ethanol/enzyme/chemical-intensive quercetin train rather than utilities alone. This distinction matters for scale-up: capital cost can be amortized over greater throughput,

whereas solvent and reagent consumption remains largely throughput-dependent unless recovery, recycling or concentration steps are intensified. The measured 93% quercetin-solvent recovery in Scenario 2 and 96% in Scenario 3 provide direct process evidence for the recycle assumption and indicate a lower solvent make-up burden for the integrated quercetin train. The base-case NPV and IRR values were calculated using the TEA model described above; the solvent-recovery measurements were used to interpret variable-cost exposure and recycle performance. The corresponding base-case NPV and IRR comparison is shown in Fig. 2.

3.3 Revenue and profitability

At the documented practical yields and selling prices, annual revenue increased from approximately INR 3.005 crore in Scenario 1 to INR 9.725 crore in Scenario 2 and INR 12.725 crore in Scenario 3. Scenario 3 therefore generated more than four times the revenue of the anthocyanin-only process. The economic advantage of the integrated design remained evident even after accounting for higher capital and operating costs: the base-case NPV increased from INR 0.18 crore in Scenario 1 and INR 2.64 crore in Scenario 2 to INR 11.15 crore in Scenario 3, while IRR increased from 10.64% and 13.75% to 19.25%.

These results show that the value of cascade processing lies in revenue stacking and more complete feedstock utilization rather than in low operating cost. The anthocyanin-only route remains close to the minimum attractiveness threshold and is therefore sensitive to modest product-price reductions. The quercetin-only route is stronger but requires disciplined control of variable costs. By contrast, the integrated route creates the largest margin between project return and the 10% discount benchmark and therefore provides the greatest headroom against adverse cost or price movement. This interpretation is consistent with broader biorefinery literature, where multiproduct portfolios can improve fixed-asset utilization and reduce dependence on a single commodity, provided downstream separation does not become disproportionately expensive (Pérez-Almada et al., 2023). The solvent-recovery measurements further support this interpretation: Scenario 3 recovered 96% of the quercetin solvent compared with 93% in Scenario 2, and the recovered ethanol concentration was 47% rather than 46%. This combination lowers relative fresh-solvent makeup and reconditioning demand in the integrated route and strengthens its operating resilience while remaining consistent with the base-case profitability calculations.

3.4 Sensitivity and scale effects

Plant throughput and product selling price were the most influential variables. For Scenario 1, reducing the anthocyanin-rich powder selling price from INR 5,000 to INR 4,000 kg^{-1} changed NPV from INR 0.18 crore to − 3.25 crore, while increasing the price to INR 6,000 kg^{-1} raised NPV to INR 3.6 crore. Increasing throughput from 500 to 1,500 kg day^{-1} shifted NPV from − 6.33 to 6.7 crore and increased IRR to 18.59%. The anthocyanin-only configuration is therefore economically feasible only when adequate scale and product value are simultaneously maintained.

For Scenario 2, quercetin selling price had an even larger absolute effect: NPV changed from − 8.46 crore at INR 3,600 kg^{-1} to INR 2.64 crore at INR 4,500 kg^{-1} and INR 13.73 crore at INR 5,400 kg^{-1}. Throughput

had a similarly strong effect, with NPV increasing from − 5.1 crore at 500 kg day^{-1} to INR 10.37 crore at 1,500 kg day^{-1}; IRR reached 22.78% at the larger scale. The measured 93% quercetin-solvent recovery, with 46% ethanol in the recovered stream versus 50% in the fresh solvent, establishes a practical Scenario 2 baseline; commercial operation should at least sustain this performance because any deterioration would increase solvent make-up and erode NPV and IRR.

Scenario 3 showed the strongest scale response. NPV rose from − 4.3 crore at 500 kg day^{-1} to INR 11.15 crore at 1,000 kg day^{-1} and INR 26.57 crore at 1,500 kg day^{-1}. The base-case IRR of 19.25% increased to 30.35% at 1,500 kg day^{-1}. Production cost was also important: a 20% increase reduced IRR to 12.74%, whereas a 20% reduction increased it to 25.35%. Thus, commercial viability depends on a coordinated strategy of scale, market qualification and cost intensification rather than on one variable alone. The 96% quercetin-solvent recovery in Scenario 3, together with a recovered ethanol concentration of 47% versus the original 50%, gives the integrated route a stronger solvent-efficiency position than Scenario 2 (93% recovery; 46% ethanol), which should reduce its sensitivity to solvent make-up cost at equivalent throughput. Key sensitivity outcomes are summarized in Table 4.

Table 4
Key sensitivity outcomes.

Scenario	Variable	Low case	Base case	High case
S1	Anthocyanin price (INR kg^{-1}) / NPV (INR crore)	4,000 / −3.25	5,000 / 0.18	6,000 / 3.60
S1	Capacity (kg day^{-1}) / NPV (INR crore)	500 / −6.33	1,000 / 0.18	1,500 / 6.70
S2	Quercetin price (INR kg^{-1}) / NPV (INR crore)	3,600 / −8.46	4,500 / 2.64	5,400 / 13.73
S2	Capacity (kg day^{-1}) / NPV (INR crore)	500 / −5.10	1,000 / 2.64	1,500 / 10.37
S3	Combined selling price (INR kg^{-1}) / NPV (INR crore)	3,687 / −3.40	4,609 / 11.15	5,530 / 25.65
S3	Capacity (kg day^{-1}) / NPV (INR crore)	500 / −4.30	1,000 / 11.15	1,500 / 26.57
S3	Production cost variation / IRR (%)	−20% / 25.35%	Base / 19.25%	+ 20% / 12.74%

3.5 Screening life-cycle assessment and environmental hotspots

The utility inventory provides a first environmental comparison of the three process designs on an identical feed basis. Scenario 1 consumed approximately 40 kWh electricity, 1.08 t steam, 20 t process water and 2 t cooling water per functional unit. Scenario 2 consumed approximately 80 kWh electricity,

1.08 t steam, 10 t process water and 2 t cooling water. Scenario 3 consumed approximately 120 kWh electricity, 1.35 t steam, 10 t process water and 2.5 t cooling water. The lower process-water value for Scenarios 2 and 3 reflects the cost inventory used in the process model and should be interpreted together with the 50% ethanol-water extraction medium rather than as total circulating liquid volume. The complete utility inventory and climate proxy are summarized in Table 5, and Fig. 3 compares the resulting utility-related CO_2 proxy across scenarios.

Table 5
Screening gate-to-gate life-cycle inventory and utility-related climate indicator per 1,000 kg onion peel processed.

Indicator	**Scenario 1**	**Scenario 2**	**Scenario 3**
Electricity (kWh FU^{-1})	40	80	120
Steam (t FU^{-1})	1.08	1.08	1.35
Process water (t FU^{-1})	20	10	10
Cooling water (t FU^{-1})	2.0	2.0	2.5
Useful utility energy (GJ FU^{-1})	3.11	3.26	4.14
Electricity CO_2 (kg FU^{-1})	28.4	56.8	85.2
Steam-generation CO_2 proxy (kg FU^{-1})	196.0	196.0	245.0
Utility-related CO_2 proxy (kg CO_2 FU^{-1})	224.4	252.8	330.2
Utility-related CO_2 proxy (kg CO_2 kg^{-1} feed)	0.224	0.253	0.330

By absolute utility use, the feed-basis ranking was S1 < S2 < S3. This ranking does not, however, represent overall environmental superiority because the scenarios deliver different product portfolios from the same quantity of feed. Scenario 3 produces two high-value fractions and retains a residual biomass stream for further valorization, whereas single-product routes allocate the process burden to fewer products. A full comparative LCA would therefore require mass or economic allocation, or system expansion, across coproducts. The integrated route may consequently deliver a lower impact per unit of recovered bioactive value even though its utility-related impact per tonne of feed is higher.

Beyond the utility-related CO_2 proxy, measured solvent recovery provides an additional environmental discriminator. The anthocyanin extraction medium was recovered at 96% in Scenario 1 and in the first stage of Scenario 3. For quercetin extraction, Scenario 2 recovered 93% of the solvent, corresponding to a 7% unrecovered fraction, whereas Scenario 3 recovered 96%, corresponding to a 4% unrecovered fraction. The recovered quercetin solvent contained 46% ethanol in Scenario 2 and 47% in Scenario 3 versus 50% in the fresh solvent, showing that solvent recovery and solvent strength are related but

distinct scale-up variables. These measured values indicate that the integrated route should require less fresh solvent make-up than the stand-alone quercetin route, although some ethanol reconditioning remains necessary. Because upstream ethanol production was excluded from the present utility-related CO_2 proxy, this benefit is not numerically captured in Fig. 3 or Table 5. Concentration and drying still create substantial thermal demand; Scenario 3 already requires approximately 25% more steam than Scenarios 1 and 2. Heat integration, mechanical vapor recompression, lower-temperature vacuum concentration and renewable or biomass-derived steam are therefore technically relevant development options. Importantly, these interventions remain aligned with the economic sensitivity results because they target the same utility- and production-cost variables that influence NPV and IRR.

3.6 Integrated eco-economic interpretation

An eco-economic decision cannot be based on either IRR or energy demand alone. Scenario 1 has the lowest resource intensity, but its base IRR (10.64%) only marginally exceeds the 10% benchmark, and its NPV becomes negative under a 20% price reduction. Scenario 3 has the highest utility-related CO_2 proxy (approximately 330 kg CO_2 per tonne of feed), but it also provides the highest base NPV and IRR and the greatest utilization of the onion-peel matrix. The preferred development pathway is therefore to retain the multiproduct configuration while engineering down the solvent- and energy-intensive steps, rather than sacrificing the revenue and biomass-utilization advantages of integration.

Four development priorities emerge from the combined analysis. First, the measured recovery baseline should be converted into a controlled operating specification: 96% extraction-medium recovery for anthocyanin processing, 93% quercetin-solvent recovery in Scenario 2, and 96% quercetin-solvent recovery in Scenario 3. The associated ethanol-strength drift (46% and 47% in the recovered quercetin solvent versus 50% in the fresh solvent) shows that recovery percentage alone is insufficient; recycle quality and the ethanol make-up required to restore extraction strength should also be monitored. Second, product specifications should be tied to defensible purity ranges, stability requirements and customer segments so that TEA selling prices can be supported by market qualification. Third, the plant should be located near stable onion-processing clusters and sized for high annual utilization; the strong improvement at 1,500 kg day^{-1} demonstrates the benefit of fixed-cost absorption. Fourth, the residual biomass should be upgraded beyond low-value disposal where feasible, with pectin and other fiber-rich fractions representing logical candidates for a subsequent cascade step. Together, these measures provide a coherent route for increasing both economic resilience and resource efficiency.

3.7 Future scale-up and commercial translation pathway

The present feasibility assessment established a common engineering, economic, and environmental-screening basis for the three process configurations and identified Scenario 3 as the preferred candidate for further development. Future work should therefore focus on technology maturation and commercial translation rather than extending the scope of the current screening analysis.

The first priority is repeated-batch or continuous pilot/demonstration operation of Scenario 3 under an integrated mass balance. This stage should confirm that the observed 96% anthocyanin extraction-medium recovery and 96% quercetin-solvent recovery can be sustained across consecutive campaigns, while quantifying ethanol make-up needed to restore the recovered quercetin solvent from 47% to the original 50% ethanol strength. Parallel benchmarking against the stand-alone Scenario 2 baseline (93% solvent recovery; 46% ethanol in the recovered solvent) would establish whether the integrated configuration consistently retains its solvent-efficiency advantage. The same campaigns should verify batch-to-batch anthocyanin- and quercetin-rich powder yields and purity while quantifying enzyme and chemical consumption, filtration performance, concentration/drying energy, wastewater generation, and product consistency. In parallel, engineering studies should evaluate solvent-recovery integration, recycle conditioning, heat recovery, lower-temperature concentration and low-carbon steam/electricity. Product-development work should establish batch-to-batch purity, stability, safety, and customer-specific quality specifications, and should validate the TEA selling-price assumptions against buyer-supported price ranges or offtake evidence.

A second development stream should extend the cascade beyond the two bioactive fractions. The remaining pectic/cellulosic solids provide a logical third-product opportunity, particularly for pectin or fiber-rich ingredients, and should be evaluated only after their incremental yield, quality, equipment demand and market value are experimentally established. Once demonstration-scale mass and energy balances are available, the screening environmental model should be upgraded to an ISO 14040/14044-compliant LCA (International Organization for Standardization, 2006a, 2006b) incorporating measured solvent losses, enzymes and chemicals, actual boiler fuel and efficiency, transport, wastewater treatment, avoided-disposal scenarios and coproduct allocation. The same validated dataset can support a bankable financial model using vendor quotations, working capital, financing structure, depreciation and salvage assumptions, together with probabilistic uncertainty analysis. These activities represent the next technology-maturation stage and do not alter the comparative conclusion reached here under the stated common assumptions.

4. Conclusions

This study establishes an experimentally anchored eco-economic basis for selecting a scale-up pathway for onion-peel valorization. At 1,000 kg day^{-1}, the single-product routes required lower fixed capital but showed weaker economic resilience, whereas sequential co-recovery increased base-case NPV to INR 11.15 crore and IRR to 19.25%. Increasing throughput to 1,500 kg day^{-1} raised the integrated-process IRR to 30.35%, confirming scale and plant utilization as central design variables. Solvent-recovery performance also favored the integrated configuration: anthocyanin extraction-medium recovery was 96% in Scenarios 1 and 3, while quercetin-solvent recovery increased from 93% in Scenario 2 (46% ethanol in the recovered solvent versus 50% in the fresh solvent) to 96% in Scenario 3 (47% versus 50%). The screening environmental assessment showed that the utility-related CO_2 proxy increased from approximately 224 to 330 kg CO_2 per tonne of feed from Scenario 1 to Scenario 3, primarily because of

higher electricity and steam demand. Nevertheless, Scenario 3 recovers more value from the same biomass and provides the strongest platform for further cascade development. The integrated configuration is therefore the preferred candidate for technology maturation, with the next stage focused on sustaining the observed 96% solvent-recovery performance, controlling recycled ethanol strength and make-up demand, heat integration and low-carbon utilities, product-specification and market qualification, and valorization of the residual pectic/cellulosic stream. A full ISO 14040/14044-compliant LCA and bankable financial appraisal can then be performed using demonstration-scale inventories, vendor quotations and site-specific logistics. Overall, the analysis provides a defined basis for technology maturation and commercial translation under the stated process, economic, and screening-environmental assumptions.

Declarations

Conflict of interest:

The authors declare no competing financial interests or personal relationships that could have influenced the work reported in this article.

Ethics statement

This study did not involve human participants, vertebrate animals, or human-derived materials; therefore, ethics approval was not required.

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Author Contribution

Chandan Kumar Sahu: Conceptualization, Methodology, Investigation, Data curation, Visualization, Writing – original draft, Writing – review and editing. Amit Arora: Conceptualization, Supervision, Validation, Project administration, Writing – review and editing.

Data availability:

The numerical data supporting the findings are reported in the article and Supplementary Information. Additional raw experimental records are available from the corresponding author upon reasonable request.

References

1. Abd-ElSalam H-AH, Gamal M, Naguib IA, Al-Ghobashy MA, Zaazaa HE, Abdelkawy M (2021) Development of green and efficient extraction methods of quercetin from red onion scale wastes using factorial design for method optimisation: A comparative study. Separations 8(9):137. https://doi.org/10.3390/separations8090137
2. Agricultural and Processed Food Products Export Development Authority (n.d.). Fresh onions. Government of India. https://apeda.gov.in/FreshOnions
3. Bains A, Sridhar K, Singh BN, Kuhad RC, Chawla P, Sharma M (2023) Valorization of onion peel waste: From trash to treasure. Chemosphere 343:140178. https://doi.org/10.1016/j.chemosphere.2023.140178
4. Benito-Román Ó, Alonso E, Cocero MJ, Beltrán S, Sanz MT (2020) Subcritical water extraction of phenolic compounds from onion skin wastes (Allium cepa cv. Horcal): Effect of temperature and solvent properties. Antioxidants 9(12):1233. https://doi.org/10.3390/antiox9121233
5. Central Electricity Authority (2025) CO_2 Baseline Database for the Indian Power Sector: User Guide, Version 21.0. Government of India. Ministry of Power
6. Cho HH, Strezov V, Jiang Y, Evans TJ (2025) A review on optimisation, cost and environmental sustainability of biomass supply and biomass pre-treatment. Ind Crops Prod 218:122573. https://doi.org/10.1016/j.indcrop.2025.122573
7. Choi IS, Cho EJ, Moon J-H, Bae H-J (2015) Onion skin waste as a valorization resource for the by-products quercetin and biosugar. Food Chem 188:537–542. https://doi.org/10.1016/j.foodchem.2015.05.028
8. Duggal M, Singh DP, Singh S, Khubber S, Garg M, Krishania M (2024) Microwave-assisted acid extraction of high-methoxyl kinnow (Citrus reticulata) peels pectin: Process, techno-functionality, characterization and life cycle assessment. Food Chemistry: Mol Sci 9:100213. https://doi.org/10.1016/j.fochms.2024.100213
9. Intergovernmental Panel on Climate Change (2006) 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 2: Energy. IGES, Japan
10. International Organization for Standardization (2006a) ISO 14040:2006 Environmental management—Life cycle assessment—Principles and framework. ISO
11. International Organization for Standardization (2006b) ISO 14044:2006 Environmental management—Life cycle assessment—Requirements and guidelines. ISO
12. Jang M, Asnin L, Nile SH, Keum YS, Kim HY, Park SW (2013) Ultrasound-assisted extraction of quercetin from onion solid wastes. Int J Food Sci Technol 48(2):246–252. https://doi.org/10.1111/j.1365-2621.2012.03180.x
13. Joković N, Matejić JS, Zvezdanović J, Stojanović-Radić Z, Stanković N, Mihajilov-Krstev T, Bernstein N (2024) Onion peel as a potential source of antioxidants and antimicrobial agents. Agronomy 14(3):453. https://doi.org/10.3390/agronomy14030453

14. Pérez-Almada D, González-Delgado Á-D, Kafarov V (2023) Integrated techno-economic and environmental assessment of biorefineries: A review of the last decade of research. Sustainable Energy Fuels 7:4892–4912. https://doi.org/10.1039/D3SE00405H
15. Peters MS, Timmerhaus KD, West RE (2003) Plant design and economics for chemical engineers, 5th edn. McGraw-Hill
16. Purohit P, Dhar S (2015) Biofuel roadmap for India. UNEP DTU Partnership
17. Sagar NA, Pareek S (2020) Onion (Allium cepa L.) peel: A review on bioactive compounds and biomedical activities. Food Res Int 132:109114. https://doi.org/10.1016/j.foodres.2020.109114
18. Sahu CK, Kumar V, Bayineni S, Arora VK, A., Kadeppagari R-K (2025) Microwave and enzyme-based green combinatorial process for the improved extraction of quercetin from rose onion peel. Food Bioscience 64:105991. https://doi.org/10.1016/j.fbio.2025.105991
19. Samota MK, Sharma M, Kaur K, Sarita, Yadav DK, Pandey AK, Tak Y, Rawat M, Thakur J, Rani H (2022) Onion anthocyanins: Extraction, stability, bioavailability, dietary effect, and health implications. Front Nutr 9:917617. https://doi.org/10.3389/fnut.2022.917617
20. Stoica F, Rațu RN, Velești ID, Stănciuc N, Râpeanu G (2023) A comprehensive review on bioactive compounds, health benefits, and potential food applications of onion (Allium cepa L.) skin waste. Trends Food Sci Technol 141:104173. https://doi.org/10.1016/j.tifs.2023.104173
21. Tena N, Asuero AG (2022) Up-to-date analysis of the extraction methods for anthocyanins: Principles of the techniques, optimization, technical progress, and industrial application. Antioxidants 11(2):286. https://doi.org/10.3390/antiox11020286
22. Towler G, Sinnott R (2021) Chemical engineering design: Principles, practice and economics of plant and process design, 3rd edn. Butterworth-Heinemann
23. Turton R, Bailie RC, Whiting WB, Shaeiwitz JA, Bhattacharyya D (2012) Analysis, synthesis, and design of chemical processes (4th ed.). Pearson

Figures

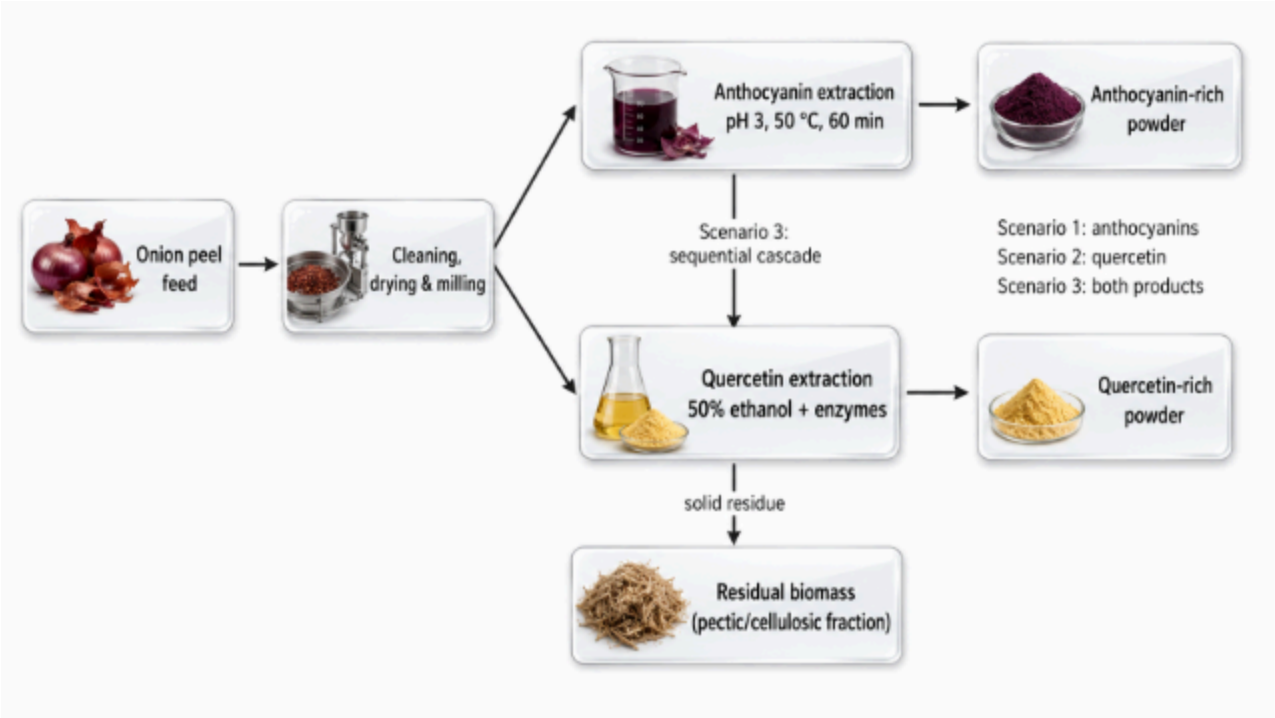


Figure 1

Conceptual process configuration for single-product and sequential onion-peel biorefinery scenarios.

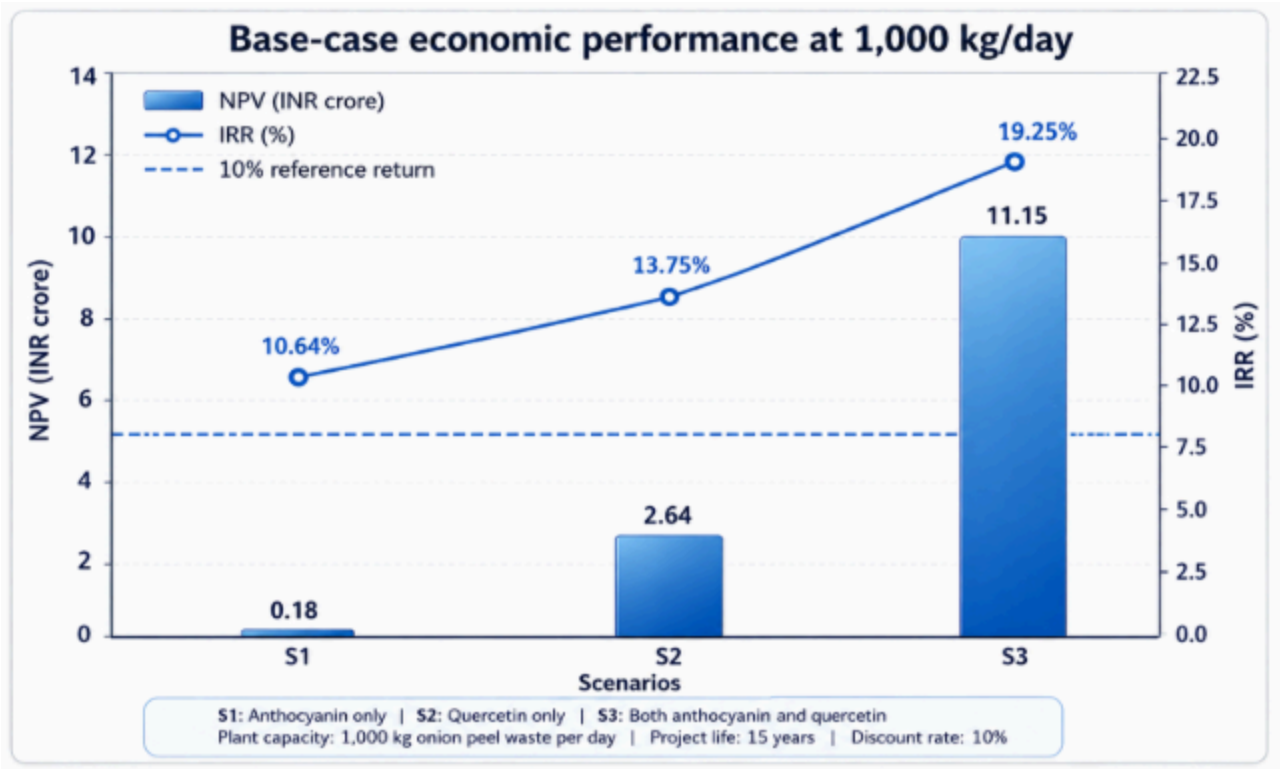


Figure 2

Base-case NPV and IRR for the three process configurations. The dashed line marks the 10% reference return used in the techno-economic analysis.

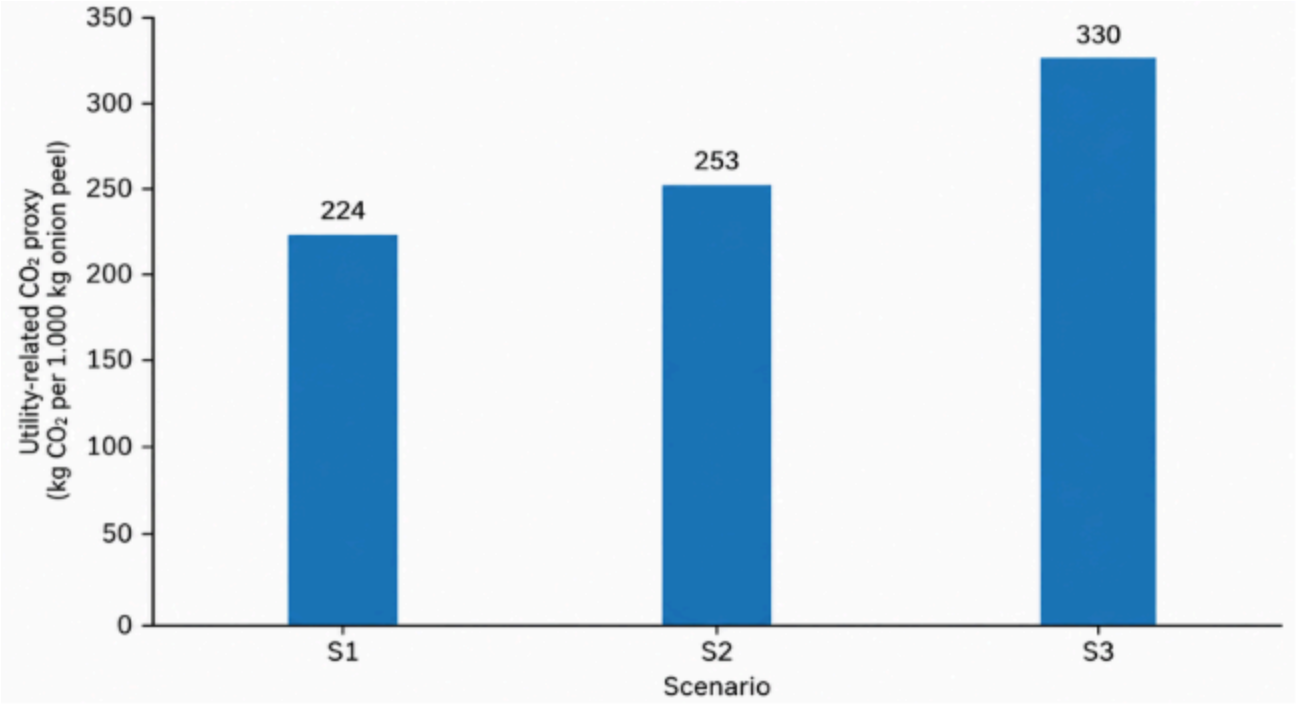


Figure 3

Screening gate-to-gate utility-related CO_2 proxy. Values include only Indian-grid electricity and natural-gas-derived steam; upstream solvent and chemical burdens are excluded.

Supplementary Files

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- SupplementaryInformationV6.docx