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Techno-eco-environmental assessment of dry fractionation of protein concentrates from yellow peas with different pre-treatment methods: An eco-efficiency approach

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A B S T R A C T

For holistic and concise decision support, it is essential to assess the sustainability of pea protein production pathways from the technical, economic, and environmental perspectives. Although regarded as the most sustainable protein extraction process, sustainability assessment of different dry fractionation pathways has not yet been carried out. To address this limitation, this study carried out a comparative techno-eco-environmental assessment of three different dry fractionation scenarios, a baseline, and two pathways with upstream pre-treatment methods of Radio Frequency (RF) treatment and Infrared Radiation (IR) treatment. Process Separation Efficiency (PSE), Life Cycle Assessment (LCA), and Techno-economic Assessment (TEA) were performed. Findings from the study showed that the RF-treated and IR-treated pea seeds produce higher yields of protein concentrates with higher protein content, as compared to the baseline. However, the higher protein separation efficiency could not comparatively offset the capital costs, processing costs, and higher energy demand associated, causing it to be outperformed by the baseline, in the economic and environmental dimensions. Although the IR treatment pathway performed better than RF treatment environmentally, it performed the least at the economic criteria. Overall, performance levels carried out using economic and protein quality value improvement for eco-efficiency assessment showed that it is very salient to consider all these three criteria integratively when assessing the sustainability performance of protein extraction pathways to identify trade-offs amongst the different dimensions. Moreover, competitive advantage played a key role in the eco-efficiency performance levels. We therefore recommend that further studies to be conducted including the product techno-functionality for a broader and more holistic perspective.

1. Introduction

The inception of the sustainability paradigm has caused the need to assess or account for the economic and environmental performances of existing and novel production processes and product systems towards their total adoption and commercialism (Tidåker et al., 2021) Alongside, in the past few decades, plant-based protein processing has also gained substantial attention to their great contribution to the reduction of environmental impact and healthy dietary patterns when used to augment or replace traditional animal-based protein, which has seen some levels of repudiation due to the large environmental impacts and health risks associated with their production and consumption (Vogelsang-O'Dwyer et al., 2021). Peas, among other pulses, are the most attractive plant-based protein sources owing to their high protein content and excellent techno-functional and nutritional qualities (Apaiah and Hendrix, 2005).

Pea proteins are produced by two major production pathways, thus, the dry and wet fractionation processes. The dry fractionation method has gained much attention in the past few years as it is very sustainable since it requires fewer steps and eliminates the use of water, chemicals, and energy for drying although has a lower protein yield and product purity as compared to the protein isolates produced by the wet fractionation method. While dry fractionation required 3.4 MJ per kg of protein recovered, the wet fractionation method required 54 MJ per kg protein recovered (Schutyser et al., 2015). Dry fractionation of peas to

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List of abbreviations

CAPEX –	Capital Expenditure
DCB –	Dichlorobenzene
EE –	Eco-efficiency
FCI –	Fixed Capital Investment
FRS –	Fossil Resource Scarcity
GWP –	Global Warming Potential
HCT –	Human Carcinogenic Toxicity
IR –	Infrared Radiation
LCA –	Life Cycle Assessment
MCSP –	Minimum Concentrate Selling Price
NFW –	Net Future Worth
NPV –	Net Present Value
OPEX –	Operating Expenses
PI –	Profitability Index
PPC –	Plant Physical Costs
PSE –	Protein Separation Efficiency
REE –	Relative Eco-efficiency
RF –	Radio Frequency
ROI –	Return on Investment
TEA –	Techno-economic Assessment
TEPC –	Total Equipment Purchase Costs
TCI –	Total Capital Investment
TOR –	Turn Over Ratio
WC –	Water Consumption
VVM –	Volume (of air) per Volume (of classifier) per Minute

produce concentrate has also been reported to contribute up to a 93% decrease in global warming potential as compared to the conventional wet fractionation method (Lie-Piang et al., 2021). Aside from being environmentally sustainable, products from the dry fractionation process, pea protein concentrates, are rich in fiber and other nutritional factors, and they contribute immensely to the nutritional quality of pea protein-based food products when used as food ingredients (Reinkensmeier et al., 2015). Dry fractionated pea proteins have proven to exhibit excellent and improved solubility, emulsifying, and foaming properties compared to wet-fractionated isolates. This is attributed to the absence of chemicals, pH-shifting, drying, and other thermal treatments such as pasteurization which can sometimes negatively alter the (natural) functionality of the proteins (Tabtabaei et al., 2023). On the other hand, dry fractionated protein concentrates with less protein purity (50–55%) and some fiber, starch, anti-nutrients, flavor precursors and microbial contaminants in some cases can hinder certain food applications compared to wet fractionated protein isolates.

Over the last decade, upstream pre-treatment methods which include dry, thermal, wet, and enzymatic treatments amongst others have been identified, developed, and proven to reduce energy requirement for milling, through initial disruption of the cotyledon matrix and increase protein separation efficiency and improve product quality and functionality needed for certain food applications (Efe and Sevdin, 2022; Laing et al., 2023). For dry fractionation, thermal pre-treatment methods are very attractive since they are generally less time-consuming and moreover, requires little or no addition of water, chemicals or other solutions which would require an energy-consuming step, drying, at the end. Aside from post-processing efficiency benefits gained from heat-treated pulse seeds and flours, thermal treatment also significantly improve the nutritional quality of and digestibility of pulses by inactivating or eliminating heat-labile anti-nutrients (Patterson et al., 2017) and improving flavor by inactivating enzymes like lipoxygenases that cause enzymatic breakdown of lipids to produce off-flavors (Roland et al., 2016). Since there is no pasteurization or kill-step involved in the traditional dry fractionation process. Incorporation of thermal pre-treatment step with whole or dehulled seeds, or with milled flours further provides the advantage of reducing microbial load to improve product safety. Techno-functional modifications to the thermal treated flours and protein concentrates have to be investigated in parallel to identifying the type and optimal heat treatment condition in order to cater the desired product applications using these thermal treated ingredients (Chao and Aluko, 2018).

The two most common thermal pre-treatment methods that have been applied in the food processing industry are the Radio Frequency (RF) treatment and Micronization or Infrared Radiation (IR) treatment (Marra et al., 2009). Altering some functional properties of plant-based proteins by using RF heating have shown to increase oil absorption, water absorption, and emulsifying activity and improve nutritional quality (Madaraboina et al., 2021). The RF treatment have also improved nutritional factors and decreased anti nutritional factors such as tryptic acid content, lipoxygenase amongst others. (Bellido et al., 2003; Scanlon et al., 2005). Pre-treatment of pigeon peas by IR has also shown a decrease in husk/cotyledon adhesion strength, decrease in milling time and increase in ease of splitting of pulses during milling (Wood et al., 2022). Protein isolates extracted from micronized dehulled black gram showed excellent emulsifying and oil-water binding capacities (Kamani et al., 2021).

Although there is evidence to support certain quality, safety aspects and yield improvement by these pre-treatment methods, data on their economic and environmental performances, as applied to the dry fractionation of pea proteins or pulses in general, is currently lacking in literature. Furthermore, sustainability assessments carried out to analyse the economic and environmental performances of pea protein fractionation processes revealed that most studies looked independently on the different dimensions, thus either performing a techno-economic assessment (TEA) or a life cycle assessment (LCA). Moreover, there is no study that applied the eco-efficiency assessment tool to compare the sustainability performance of fractionation scenarios (Allotey et al., 2023).

Eco-efficiency is a sustainability assessment concept that aims to reduce the consumption of resources and raw materials, as well as the environmental impact while maintaining or enhancing the value of the manufactured product (Maxime et al., 2006). Eco-efficiency allows the integration of economic and environmental results into a ratio or scores known as eco-efficiency indicators (Carrasquer et al., 2017; Sanjuan et al., 2011). In all these, the pea-protein processing field, has not seen the application of eco-efficiency approaches for the integrative assessment of the economic and environmental performance dynamics of fractionation of pea concentrates. In this study, another eco-efficiency metric is explored which is based on the quality of the concentrate, the protein purity.

To this end, this study is presented under 5 sections including the Introduction. Section two captures the methodologies employed including the pilot-scale production process, LCA, TEA, and eco-efficiency methods used. Technical performances of the three different dry fractionation processes, results from economic and environmental assessments, as well as the eco-efficiency indicators, are presented and discussed under Section 3. The strengths and limitations of the present study are presented in Section 4 and the major findings and concluding remarks are highlighted under Section 5. Findings from this study would contribute immensely to the body of knowledge regarding the holistic sustainability performance of different pea protein fractionation methods.

2. Material and methods

This section describes the materials and methods applied to carry out the pilot scale fractionation processes and the subsequent process efficiency analysis, techno-economic and life cycle assessments based on primary data obtained from the pilot production. Finally, eco-efficiency performance of each process is assessed and compared to the baseline.

2.1. Dry fractionation process

The baseline process begins with a dehulling step where the hulls (rich in fibre) are separated from the cotyledon (protein and starch) prior to milling and air-classification, as shown in Fig. 1. The non-treated yellow pea seeds, CDC Lewochko variety sourced from Saskatoon, SK, Canada, were dehulled using a stone mill (Stone Mill MJSG, Bühler Group, Uzwil, Switzerland) at a rate of 1 ton/per hour. The hulls were separated and collected with the help of an aspirator at an air volume aspiration rate of 5 m^3/min. The dehulling efficiency was then determined by the percentage of cotyledon produced (dhal yield). Prior to milling into fine flour for fractionation, the dehulled seeds were coarsely milled into grits for easier and more efficient milling. This process was carried out using a hammer mill (Comminutor, Fitz®Mill, The Fitz Patrick Company, Illinois, USA) at 1500 rpm for at a rate of 20 kg/hr. The pre-milled grits were further milled in an air classifier mill (CLM-18 SS, Prater Industries Inc., Bolingbrook, USA). The operating conditions of the milling was characterized by a mill speed set at 80% (2880 rpm), classifier fan speed set at 50% (1800 rpm), air flow rate of 140 cfm, and a feed rate of 10 kg/h. The flour was then transferred to the air classification unit (Mini Split, Prater Industries Inc., Bolingbrook, USA) where fractionation into a fine fraction (protein concentrate) and a coarse fraction (starch-rich fraction) took place. The fractionation was carried out at 40% classifier with a feed rate of 12 kg/h and secondary air flowrate of 3 VVM (volume of air per volume of air classifier unit per minute). Fine fractions were collected as the protein concentrates and protein yield, moisture content, protein content and protein separation efficiency were determined (Pelgrom et al., 2013).

For the other two scenarios, the baseline process is the same for the post-treatment downstream processing. The process description for the pre-treatment methods is presented in the next sections.

2.1.1. Pre-treatment

This was carried out by passing tempered pea seeds (same amount and same yellow pea starting material as baseline) through a pilot scale RF system. Processing parameters of the RF treatment were as follows: frequency of 27.12 MHz, conveyor speed of 0.17 m/min using 1.5-m conveyer belt exposing to electrodes, material depth of 30 mm, electrode gap of 86.9 mm, and anode current and grid current of 1.79 and 0.56 A, respectively. The outfeed temperature (the temperature at which seeds exit the conveyer belt) and electrode temperature (the temperature which the seeds were exposed to) were 84.4 °C and 100.1 °C, respectively. The moisture contents of peas before and after RF treatment were 13.6 and 10.2 %, respectively. The pea seeds were not tempered prior to the RF Treatment because the moisture content was suitable. However, tempering operation where the pea seeds were treated with water to increase the moisture content to a target range of 12–13% was carried out prior to dehulling.

2.1.2. IR pre-treatment

For the IR treatment, the IR Treatment equipment from the Micronizing Company UK Ltd. (Sufolk, UK. Model A 156,379-B0, with FMC Syntron ® vibrating conveyor and feeder from Bulk Handling Equipment, Homer City, PA, USA), was used. The feed was set at setting 55 and the conveyor was set at setting 37–45. The IR source was propane-fired infrared burners. The burners (emitter) were set 17 cm from the sample. Prior to the IR treatment, the seeds were tempered from 13.6% to 15.5% moisture content. The tempered peas seeds were passed through the infrared processing unit and exposed to reach a temperature of 125–130 °C for a residence time of 60–90 s. The moisture content of tempered seeds and final product were recorded as 15.5% and 10.6%, respectively. Treated seeds were tempered to 12–13% moisture prior to dehulling.

2.2. Techno-economic assessment (TEA)

Material and energy balances were estimated using Microsoft Excel 365 (Microsoft Corporation, Redmond, Washington) based on the primary process data obtained from the pilot scale production. Using the process efficiencies, residence time, energy consumption of the different units, the scenarios were scaled up to an industrial pea protein production plant with an annual processing capacity of 40,000 tonnes of yellow peas. The plant is scheduled to operate for 8000 h per year with the remaining time allocated for downtime and maintenance. The project period is assumed to be 20 years and the straight-line depreciation method was selected to estimate the depreciation value at a salvage value of 10% of fixed capital investment (Peters et al., 2003). All economic assumptions and parameters are presented in Table 1.

Table 1
Assumptions and parameters for economic assessment.

Parameter	Assumption
Annual hours of production	8000
Construction	1 year
Plant Life	20 years
Tax rate	25%
Salvage value	10% of FCI
Discount rate	7.55%
Selling price of products	
Protein concentrate	\$ 3.83/kg
Starch concentrate	\$ 1.31/kg
Hulls	\$ 0.41/kg
Utility Costs	
Electricity cost	\$ 0.15 per kWh
Water supply cost	\$ 2.0 per m^3
Raw material cost	\$ 0.47 per kg

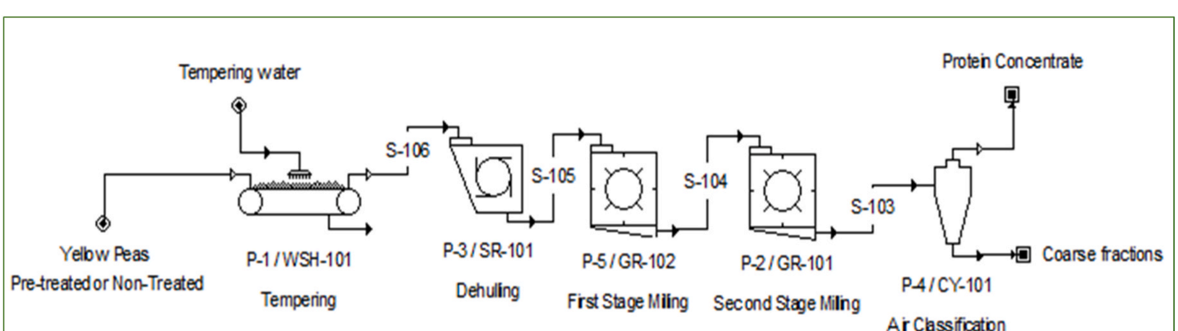


Fig. 1. Process flowsheet for dry fractionation of yellow peas. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2.2.1. Total Capital Investment (CAPEX)

The equipment purchase were estimated using vendor quotes and the six-tenth factor (Towler and Sinnot, 2008) based on the equipment capacity and costs of the pilot-scale production. From the Total Equipment Purchase costs (TEPC), piping, instrumentation, electrical, site development and storages, are estimated as a percentage of the TEPC. The sum of these costs and the TEPC makes the Plant Physical Cost (PPC). Indirect costs are then estimated as the percentage of this cost, which include design and engineering, contractor's fee, and contingencies. The Fixed Capital Investment (FCI) is then estimated as the sum of PPC and Indirect Costs. The Working Capital is estimated where the sum of these value and the FCI becomes the Total Capital Investment (TCI) (Peters et al., 2003).

2.2.2. Total operating costs (OPEX)

The total annual operating costs are estimated as a sum of direct manufacturing costs and indirect production costs. The direct production costs include variable operating cost (raw materials, utilities), and fixed operating costs (maintenance, labour, cost of supervision, plant overheads, insurance, taxes, royalties). The indirect manufacturing costs, also known as the general expenses, includes sales, research, development, and administrative expenses. Estimating these values, in terms of the percentage of the capital investment and direct production costs, are shown in the Supplementary document.

2.2.3. Profitability analysis

Profitability analysis is carried out to assess the worth of investment by estimating economic indicators such as turn over ratio (TOR), Return on Investment (ROI), etc., as these indicators incorporates capital costs, production costs and annual sales (revenue) of the plant. The Net Present Value (NPV) and Profitability Index (PI) are also estimated, which is a principal measure of the profitability of the process plant where discounted cash flows are used to account for the time value of money (Towler and Sinnot, 2008). Annual revenues are estimated from the production rates of protein concentrates, starch concentrates and hulls of each process scenario with product prices of \$3.83/kg, \$ 1.31/kg, and \$0.41/kg, respectively. All monetary values in this study are presented in Canadian Dollars.

The TOR is estimated according to the equation:

$$TOR = \frac{Gross\ Annual\ Sales}{Fixed\ Capital\ Investment} \tag{1}$$

The ROI is estimated according to the equation:

$$ROI = \frac{Annual\ Profit_{after\ tax}}{Total\ Capital\ Investment} * 100 \tag{2}$$

The NPV is estimated according to equation:

$$NPV = \sum_{t=1}^{pl} \frac{CF_t}{(1+r)^t} - TCI \tag{3}$$

The PI is estimated according to the equation:

$$PI = \frac{\sum_{t=1}^{pl} \frac{CF_t}{(1+r)^t}}{TCI} \tag{4}$$

Where CF_t is the net annual cash inflow for the year t, r is the discount rate, TCI is the Total Capital Investment.

Another indicator explored to measure the profitability of a production process is the minimum selling price of the product (Petersen et al., 2020). The Minimum Concentrate Selling Price (MCSP) is the minimum price of the protein concentrate, considering the capital and operating costs, as well as other economic factors such as tax rate, discount rate etc., below which the investment would be deemed economically unviable or at NPV = 0. This value guides industrial processors in product pricing.

2.3. Life cycle assessment (LCA)

2.3.1. Goal, scope, and functional unit

The goal of the LCA was a comparative analysis of the environmental impacts of three dry fractionation scenarios to produce pea protein based on the pre-treatment method. The functional unit selected for the analysis is based on 1 kg of protein concentrate. This functional unit is a better representative of processes being considered at the industrial scale. The geographical scope considered for the analysis is Saskatoon, SK, Canada.

2.3.2. System boundary

The system boundary precludes the environmental impacts associated with the producing the pea seeds and the end use of the products rendering the assessment a gate-to-gate approach. This is to enable the critical understanding of the processing system and more importantly how the pre-treatment methods affect the sustainability dynamics of dry fractionation. Therefore, the system boundary includes the thermal pre-treatment method, tempering, dehulling, hammer milling, air classifier milling, and air classification fractionation (Fig. 2). The two inputs include water and electricity. While water is only required at the tempering stages, electricity is an input to all the processes, as shown in Fig. 2. For the thermal treatment methods, pea seeds were tempered to about 15% moisture before IR treatment while for RF treatment, seeds were not tempered prior to pre-treatment since the initial seed moisture was already at 13.6%. Presence of moisture during thermal treatments is needed to increase internal seed temperature by oscillating water molecules in the case of RF processing. During both RF and IR treatments, water also helped in releasing off-flavor volatile compounds, reducing microbial counts, antinutrient enzymes (e.g. lipoxygenases, lipases), and also avoiding excessive drying of seeds especially in the case of IR treatment at 130–150 °C temperature range (Patterson et al., 2017).

All treated and untreated pea seeds were tempered to approximately 12% moisture prior to the dehulling and fractionation process. Tempering prior to dehulling help in effective hull removal and subsequent milling to generate a uniform cotyledon flour (Wood et al., 2022). The system boundary excluded the production/cultivation of yellow peas and activities that involve the transportation, post processing and consumption of the final products (concentrates), making it a gate-to-gate assessment.

2.3.3. Life cycle impact assessment

The data used for the life cycle assessment was based on the technical parameters obtained from the pilot scale production step. Electricity usage was calculated from the electrical parameters of the equipment. The characterized impacts were estimated using the scaled-up process requirements and data from the Ecoinvent 3.7 database (Ecoinvent, Zürich, Switzerland). The process used for the electricity was "market for electricity, medium voltage | electricity, medium voltage | APOS, S - CA-SK". The open-source life cycle assessment software, Open-LCA V1.11.0 (GreenDelta, Berlin, Germany), was used to carry out the assessment. The impact assessment used was Recipe 2016 Midpoint (H). The characterised results for all processes are used for the comparative analysis. The economic allocation method was employed because of the wide difference between selling prices of the main product (protein concentrate) and co-products (starch concentrate and hulls).

2.4. Techno-eco-environmental (eco-efficiency) analysis

Performance levels obtained from the TEA and LCA and the product quality (only protein purity, did not consider other quality parameters for this study), were used to assess the eco-efficiency performance of the three dry fractionation processing pathways. The eco-efficiency indicators were calculated using the Net Present Value (NPV) as the economic indicator and Global Warming Potential (GWP) as the environmental impact factor. In addition to this widely used economic

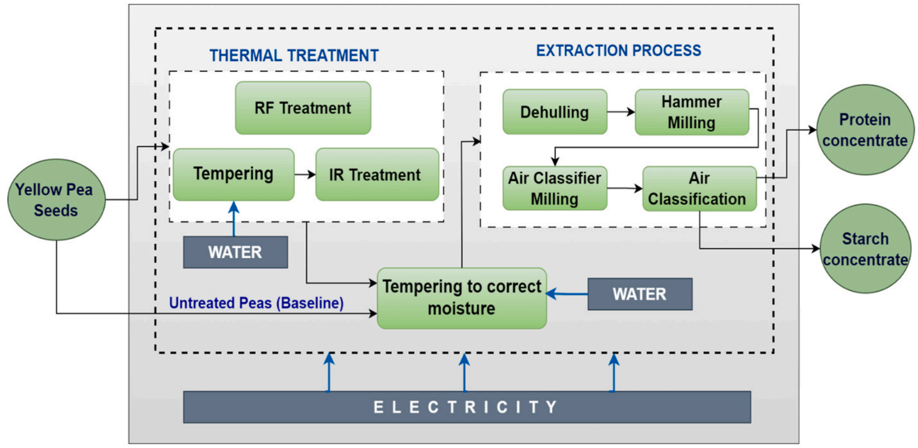


Fig. 2. System boundary for LCA

indicator, two other economic indicators were selected to measure the Eco-efficiency, thus the Net Profit (NP) and Net Future Worth (NFW) recorded for the three processing scenarios, with a constant protein concentrate price.

$$EE_{i,j} = \frac{NPV_i}{GWP_j} \tag{5}$$

Where $EE_{i,j}$, is the Eco-efficiency of process pathway $,j$, based on the economic indicator, i. NPV is the value of the Economic Indicator and is the global warming potential recorded for the processing scenario, j.

Eco-efficiency assessment also allows comparing alternative the economic and environmental performance of alternative process pathways with a reference or a baseline (Cruz et al., 2019). Therefore, the Relative Eco-Efficiency (REE) for the two pre-treatment scenarios, thus, RF Treatment and IR treatment are calculated using the equation below.

$$REE = \frac{EE_i}{EE_{i,Baseline}} \tag{6}$$

where $EE_{i,Baseline}$ is the Eco-efficiency of the Baseline process for the different economic indicators.

3. Results and discussion

This section presents and discusses the results obtained from the pilot scale production system process efficiencies, protein yield and separation efficiency. The economic and environmental results from the TEA and LCA are presented, and major findings are highlighted. For the sake of the discussion, “Baseline” represents the baseline scenario without any thermal treatment, “RF Treatment”, represents the scenario with the upstream RF treatment of pea seeds and “IR Treatment” represents the scenario with the upstream IR Treatment of the pea seeds.

3.1. Technical Performance Assessment

3.1.1. Protein yield and purity

For this study, the fractionation was carried out with the same process units and processing conditions were made constant. Therefore, process efficiencies in terms of yield, purity (dry basis), and protein shift recorded are solely attributed to the characteristics of the flour in terms of, particle size distribution, protein content, and dispersibility. The results are based on the average of two experimental trials. From Fig. 3, the RF Treatment recorded the highest protein yield of 21.9%, and 19.8% for the IR Treatment, with the Baseline recording the least protein yield of 19.2%. This generally indicates that adding thermal pre-treatment methods increased the protein yield. These results correlate with previous studies of air classification of peas that recorded protein

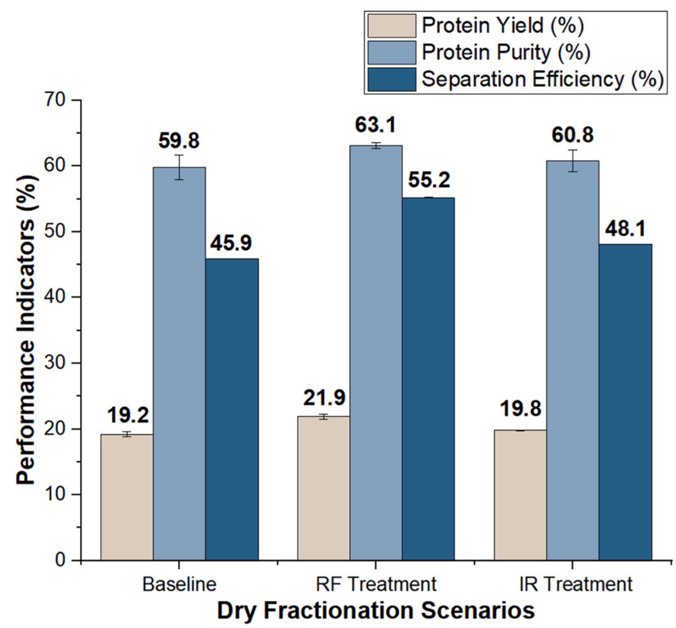


Fig. 3. Technical performance assessment of dry fractionation processes.

concentrate yields of 14%–23% (Angelisa et al., 2021; Cloutt et al., 1987; Reichert, 1982).

With regards to the protein content (on dry basis), the RF Treatment also recorded the highest protein purity of 63.1% followed by 60.8% and 59.8%, recorded for the IR Treatment and Baseline, respectively. These values also fall in the range of purity of pea protein concentrate obtained by air classification, thus 55–70 % (Allotey et al., 2022; Pelgrom et al., 2015; R.T. Tyler et al., 1981). For the particle size distribution as presented in Table 2, RF Treatment had the least $D_{0.9}$ of 17.85 μm, which shows 90% of the total particles in the concentrates have particle size of 17.85 μm or below. Since the protein particles are characterised by smaller particle size, air-classified fine fractions with the least particle size would be expected to have highest protein content among other fine fractions, at a specified quantity (same volume fraction). This was evidenced by IR Treatment, recording the second least $D_{0.9}$ of 18.45 μm, had a higher protein purity (60.8%) than the Baseline with $D_{0.9}$ of 19.6 μm recording the least protein purity of 59.8%.(Assatory et al., 2019; Pelgrom et al., 2014; Xing, 2021).

3.1.2. Protein separation efficiency

Protein separation efficiency (PSE) is defined as the percentage of

Table 2
Particle Size Distribution of fine fractions (proteins) and coarse fractions (starch).

Process Scenarios	Particle Size Distribution					
	Fine Fraction (proteins)			Coarse fractions (starch)		
	$D_{0.1}$, μm	$D_{0.5}$, μm	$D_{0.9}$, μm	($D_{0.1}$), μm	$D_{0.5}$, μm	$D_{0.9}$, μm
Baseline (No-Pretreatment)	2.05	6.02	19.60	9.82	21.50	38.65
RF Pretreatment	2.42	7.14	17.85	12.20	22.85	40.50
IR Treatment	2.55	7.51	18.45	10.90	21.35	38.15

protein in the flour that is recovered in the fine fractions (protein concentrate) and as such, dependent on the protein yield and protein content of the concentrate (R.T. Tyler et al., 1981; Reichert, 1982). Regarding the PSE, in the descending order, RF Treatment, baseline and IR Treatment recorded at 55.2%, 45.9% and 48.1%, respectively. This is expected as the RF Treatment recorded the highest protein yield and protein content. Overall, regarding the technical performances of the process scenarios, the pre-treatment methods outperformed the fractionation with untreated peas with the RF ranking best. This indicates that the RF treatment as a pre-treatment method for yellow peas, increases protein extraction efficiency by disrupting the protein-starch matrix in the cotyledon. A study on the effect of RF with electrode gap of 110 mm on pea cotyledon cells showed morphological changes that involve the slight thinning and fracturing contributing to the disentanglement of the protein-starch matrix as compared to a tightly packed cotyledons of untreated peas (Zhang et al., 2021). This is also attributed to the low depth penetrability of RF waves which disrupts the inner core structure (cotyledon) of the seeds, causing disentanglement as compared to the IR treatment which mainly affects and disrupts more of the cotyledon-hull interface by thermally degrading the gum and mucilage that binds the hulls and cotyledons (Kumar et al., 2022; Ştefănoiu et al., 2016).

To this end, further studies could be performed in optimizing the treatment to control the excessive reduction of moisture content. Moreover, studies should also be carried out to optimize the IR pretreatment method process towards producing high protein yield and purity at the downstream processing. In summary, the results from the pilot scale production shows that, the RF Treatment technically outperformed the other two scenarios, ranking first, with IR Treatment and Baseline ranking second and third, respectively. The subsequent sections discuss their economic and environmental performances.

3.2. Techno-economic performance

3.2.1. Capital investment (CAPEX)

From Fig. 4A, the baseline process recorded the least Total Capital Investment (TCI) of 8.4 M$ stemming from its simplicity and the absence of upstream pretreatment processing units as found in the other two processing pathways. The highest TCI was recorded for the IR process (22.9 M$) mainly due to the very high equipment cost of the IR treatment unit (66.3% of total purchased equipment costs). Similarly, the RF process with TCI of (17.5 M$) also had the major contributor to be the RF treatment unit (45.5% of the total purchased equipment cost). This indicates that capital costs of dry fractionation processing systems are very sensitive to the presence or absence of a thermal pretreatment section and most importantly the selection of a specific pretreatment option. Details of the other contributing costs, thus the piping, instrumentation, site development, engineering design, contingencies, working capital etc. (Thrane et al., 2017; Tidåker et al., 2021) are reported in Tab les S1 and S2in the Supplementary Material.

3.2.2. Total operating costs

From the results, the IR Treatment process had the highest total annual operating costs of 43.9 M$, followed by the RF Treatment process with 41.4 M$, due to the added number of steps and especially the high utility costs associated with the pretreatment sections (Fig. 4B). The Baseline recorded the least operating cost (35.3 M$) owing to the fewer unit operations. The breakdown of the total which describes the expenditures incurred to operate and maintain the processing plant for each scenario, is as follows.

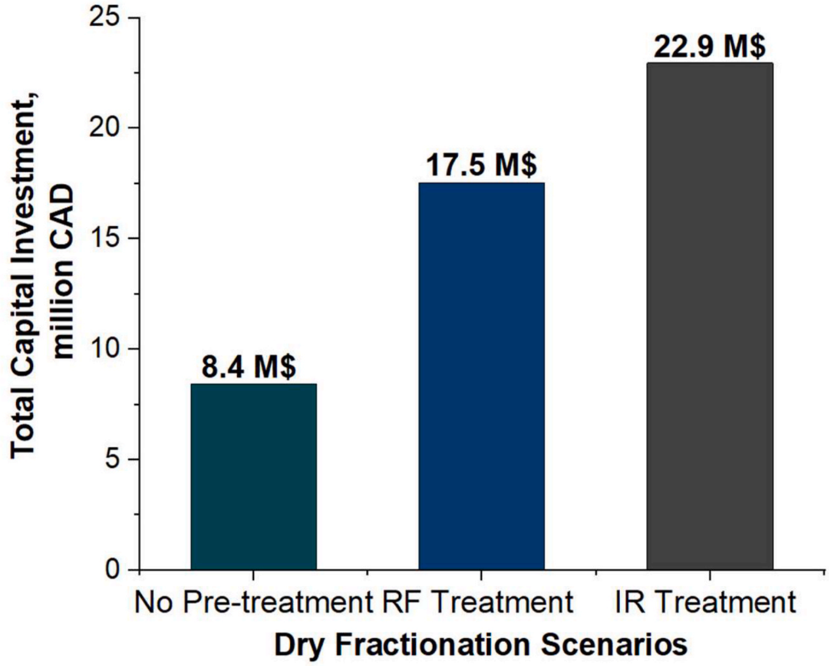
The raw materials costs, which is the same for all scenarios (18.86 M $), due to equal processing capacity (40 kt of yellow peas per annum), contributed highest to the total operating costs. Across the three scenarios it contributes to 54%, 47% and 44% of the total operating costs for the Baseline, RF Treatment, and IR Treatment, respectively. This clearly indicates that for commercial pea concentrates production plant, the overall production costs are highly dependent on the processing capacity and price of raw materials. Utility costs, electrical energy required by the dehulling and milling equipment, air blowers and classifier wheels, do not contribute much to the operating costs, thus, about 5% across all scenarios, with absolute amounts of 1.62 M$, 2.20 M$ and 2.1 M$ for the Baseline, RF Treatment, the IR Treatment, respectively. This is due to the absence of heating, cooling, drying and other energy consuming processes. Labour costs do not also contribute significantly (7–9%) owing to the small number of major unit operations (4–7), therefore requiring a small number of operators on the plant.

The maintenance costs comprising overhaul cost, spare parts and labour expenses from maintenance also contributed significantly to the total operating costs. Moreover, as it depends on the fixed capital costs (30% of FCI), there is a significant difference among the three processes: 6% (2.04 M$), 10% (3.85M$) and 14% (5.68 M$) for the Baseline, RF Treatment, and IR Treatment, respectively. The financing costs, also dependent on the capital (10% of FCI) recorded 3–5% of the total operating costs for the different scenarios. General expenses, also known as the indirect manufacturing costs, include the sales expenses, research and development, plant overheads and administrative expenses. This contributed to about 24% of the total operating costs across the scenarios: Baseline (8.41 M$), RF (9.79 M$) and IR (10.4M$). The 'other costs' made of royalties and insurance, 5% and 1% of FCI, respectively, did not contribute significantly to the total costs across all scenarios, thus less than 4%.

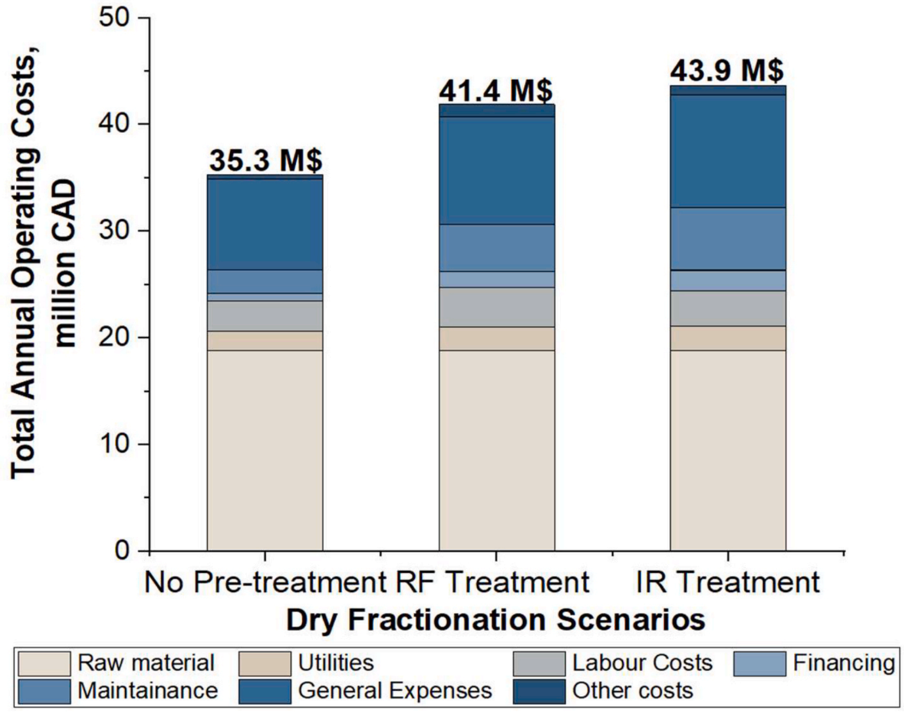
3.2.3. Total annualised production costs

The total annualised cost method is used to convert the capital investment into an annual capital charge which is added to the operating costs to estimate the overall annual production costs. For an interest rate of 10% over a 20-year project, an annual capital charge ratio of 0.117 was selected (Towler and Sinnot, 2008). As shown in Table 3, total annualised production costs estimated were 35.8 M$, 43.6 M$ and 45.9 M$ for the Baseline, RF Treatment, and IR Treatment scenarios, respectively. This is expected as both CAPEX and OPEX estimates had the same trend. Thus, the IR Treatment process being highest, followed by RF Treatment, with the lowest costs recorded by the Baseline. Production costs of processing plant can also be expressed per mass basis of main product of the plant. To this end, the annualised production costs per kg of protein concentrate (the main product), were estimated in $/kg as 6.47, 6.46 and 8.03. It is worth noting that, although, the total annual production costs of the RF Treatment are greater than the Baseline, however, per the mass basis, the RF Treatment recorded very much comparable costs (6.46) with the baseline (6.47). This is attributed to the high protein yield recorded for the RF treatment as seen in the technical performance assessment (Table 3). This clearly shows that, in terms of unit product cost, the RF Treatment process performs very well and therefore further studies to optimize the unit operation to increase the yield would go a long way to positively affect the economic dynamics.

In summary, although not a very significant difference was observed in overall operating costs across all scenarios, the major contributors to the total processing costs of were the raw material cost, maintenance



A



B

Fig. 4. Summary of cost analysis for fractionation pathways. A) Capital costs (B) operating costs.

costs and the general expenses. Details of the CAPEX and OPEX are presented in Supplementary Data Sheet.

3.2.4. *Profitability analysis*

Profitability analysis is carried out to assess the economic viability and performance of an investment as it incorporates production costs, revenues, tax rates, discount, project life, depreciation and other factors, to estimate metrics known as profitability indicators (Towler and Sinnot, 2008). The results from the total capital and operating costs, together with the economic parameters and assumptions (show in in Table 3), provided the basis for the profitability analysis. Table 3 presents the summary of the profitability indicators for the three scenarios, thus TOR, Net Future Worth, Payback period, ROI, Profitability Index and NPV. From the values measured all fall in the acceptable ranges that make a project economically feasible, therefore venturing into a dry fractionation production plant would yield profit. Breakdown of the total revenues generated is presented in the Supplementary Material.

The TOR, which measures the financial performance of the initial

Table 3
Summary of economic performance of fractionation scenarios.

Economic indicators	Baseline	RF Treatment	IR Treatment
Capital and Operating Costs			
Total Capital Investment (M$)	8.4	17.5	22.9
Total Operating Costs (M$)	35.3	41.4	43.9
Total Annualised Production Costs (M$)	36.3	43.5	45.9
Annualised Production Costs ($/kg protein product)	6.57	6.45	8.15
Profitability Analysis			
Total Revenue (M$)	53.9	59.5	54.4
Turn Over Ratio	7.69	3.99	2.88
Net Future Worth (M$)	261	246	132
Payback period (years)	1.2	2.0	3.2
Profitability Index	19.23	7.69	4.07
Net Present Value (M$)	129.5	117.1	56.5

investment in terms of ratio of the annual sales to the TCI estimated as 7.93, 3.99, and 2.88 for the Baseline, IR, and RF Treatment, respectively. This transcends into all the other profitability indicators measured, that are relative to the TCI: Profitability Index and Payback period. The pay back period (Table 3) is highest for the IR treatment (3.2 years), The RF treatment recording 2.00 years and least for the Baseline (1.2 years), stemming from the profitability index which indicates that a higher profit return increases the annual cash inflows, thereby decreasing the number of years required to pay of the investment (Peters et al., 2003).

The NPV is one of the most important profitability indicators in economic assessment as it takes into account the discounted cash flow (at 7.55% discount rate for this study) and determines the future financial performance of the project compared to the TCI (Towler and Sinnot, 2008). For this study, the Baseline recorded the highest value of 129.5 M$, followed by the RF Treatment (117.1 M$) with the least recorded by IR Treatment, 56.5 M$ (Fig. 5A). This clearly indicates that, although the pre-treatment methods show a higher process efficiency as compared to the baseline, the capital and operating costs associated with them could not be offset by the revenues generated. To this end, according to the economic performance by the different scenarios, the Baseline ranked first, RF Treatment ranked second, and IR Treatment ranked third. Moreover, although the plant cost, thus the TCI of the RF Treatment was significantly higher (108%) than the Baseline, the NPV of the Baseline was only 10.3 % higher than that of the RF Treatment. This is attributed to the relatively high protein yield which results to increased revenue generated, as well as the relatively lower difference between their operating costs, thus the RF costs were only 16% greater than that of the Baseline.

3.2.5. Sensitivity analysis

Sensitivity analysis is carried out to identify the factors (economic or technical parameters) that have greater influence on the economic dynamics of the plant. Fig. 5C presents the sensitivity of the NPV to the economic parameters: raw material cost, utility cost, pre-treatment unit cost, selling price of protein and discount rate, for the RF Treatment scenario (the other two process scenarios recorded similar outcomes). The NPV was most sensitive to the selling price of protein concentrate and cost of raw materials. where a ± 15% change in these parameters corresponds to ± 24.4% and ± 23.1% in the NPV, respectively. An equal change in the cost of the pre-treatment unit would also result to a ± 5.5% change in the NPV. Among the parameters, the utility costs were identified to be the economic parameter that has the least influence on the NPV, where a ± 15% change would result to only ± 2.5% change in the NPV.

3.2.6. Minimum Concentrate Selling Price (MCSP)

Minimum Concentrate Selling Price is a widely used economic factor to determine the profitability of a production process and aids in product pricing. From Fig. 5B, the MCSP recorded for the RF Treatment and IR Treatment were 1.47 $/kg and 2.50 $/kg, respectively. The higher MCSP for the IR Treatment is due to higher capital and processing costs as compared to the RF Treatment.

Furthermore, from the results obtained from the economic assessment, absence of a pretreatment unit caused the baseline process to perform best in the economics due to less capital and operating costs associated, as compared to the two pretreatment process pathways, which was expected. This was carried out at the same selling price of

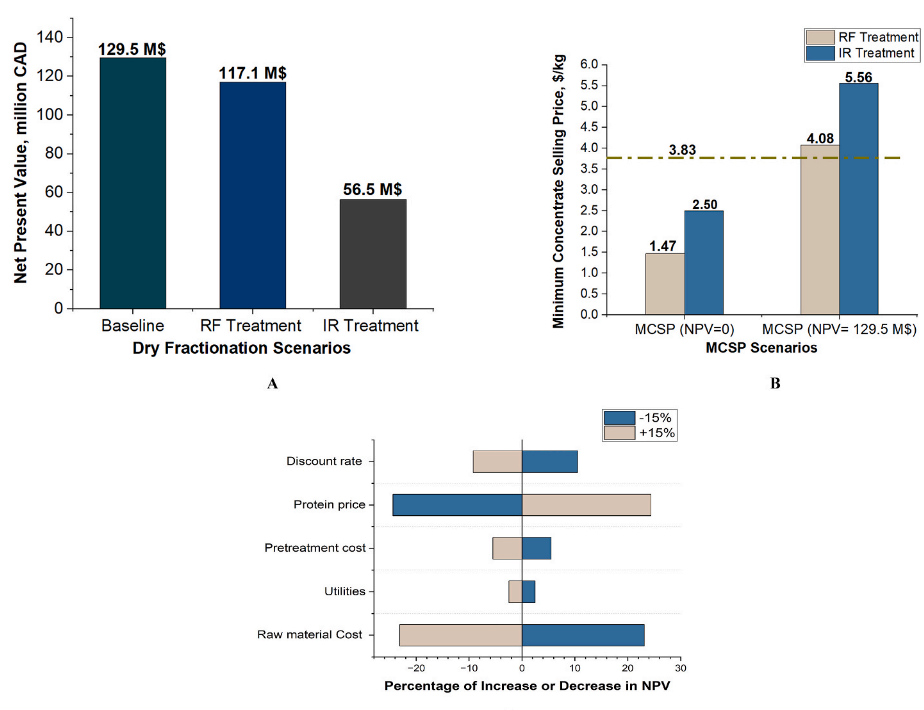


Fig. 5. Profitability and sensitivity analysis. A) Net present value. B) Minimum concentrate selling price. C)Sensitivity analysis.

protein concentrate. However, thermal pre-treatment of pulses prior to protein concentrate production has numerous benefits relating to the product quality in terms of protein content, nutritional quality, reduced ant-nutritional factors, organoleptic properties amongst others (Kumar et al., 2022; Madaraboina et al., 2021; Scanlon et al., 2005). Industrial processors, the stakeholders most inclined to the economic performance of a production plant, can alter (increase) selling price of the protein concentrate. To this end, another MSCP was estimated using the Baseline as the reference process, thus a selling price for the products from the two alternative processes, that would make the process attain an NPV of 129.5 M$.

The results for this are also displayed in Fig. 8 where the RF treatment again recorded a less MCSP of 4.08 $/kg, as compared to 5.56$/kg, recorded by the IR treatment process. The dashed lines show the initial price that was used for the base-case scenario (which is same as the price for Baseline to achieve 129.5 M$) and it is presented here to observe how the new prices compare to the old price (the relative difference). From these results, an optimal price for industrial processors who would adopt either of these pretreatment methods due to the quality upgrade and competitive advantage in terms of consumers willing to purchase their product based on the quality provided, and not going for the cheaper but of less quality, could span between the initial selling price of 3.83 $/kg and the respective MSCP (NPV = 129.5 M$) for the alternatives.

3.3. Environmental impact

3.3.1. Overall performance (scenario analysis)

Although dry fractionation has proven to be the most environmentally sustainable protein extraction process among the others, wet and hybrid, it is salient to compare the environmental implications of different dry fracationation methods in selecting the most sustainable. So far, the technical and economic aspects have been discussed, and therefore this section assesses the environmental impact of the three scenarios. Due to the absence of heating, drying, chemicals, etc., the main flow contributing to the impacts is electrical energy, which is used to drive motors for the dehulling and milling equipment, classifier wheels and air blowers. The environmental impacts of the different scenarios estimated per 1 kg of protein concentrate produced are presented in Fig. 6.

From Fig. 6, environmental impacts of the three scenarios in terms of the Global Warming Potential (GWP), Human Carcinogenic Toxicity (HCT), Fossil Resource Scarcity (FRS) and Water Consumption (WC). The overall behaviour of all the other midpoint indicators, that are not shown here (Supplementary Material) including Acidification, Eutrophication, Ecotoxicity, amongst others recorded similar perfromance in terms of the trend, and only differ by their characteristic results. For GW, the RF Treatment recorded the highest impact of 0.530 kg CO_2 eq., IR Treatment, 0.527 kg CO_2 eq, with the least impact of 0.437 kg CO_2 eq., recorded by the Baseline. The same trend is observed for HCT, thus the RF Treatment, IR Treatment and Baseline recorded, in kg 1,4 DCB eq., 0.0409, 0.0407 and 0.0338 respectively. However, for water consumption, IR treatment recorded the highest WC of 0.00453 m^3, with 0.00438 m^3 and 0.00355 m^3, being recorded RF treatment and Baseline, respectively. Comparing the overall impacts (GWP and HCT) among the three scenarios, these results are expected since the RF Treatment and IR Treatment had additional equipment which increases the electricity

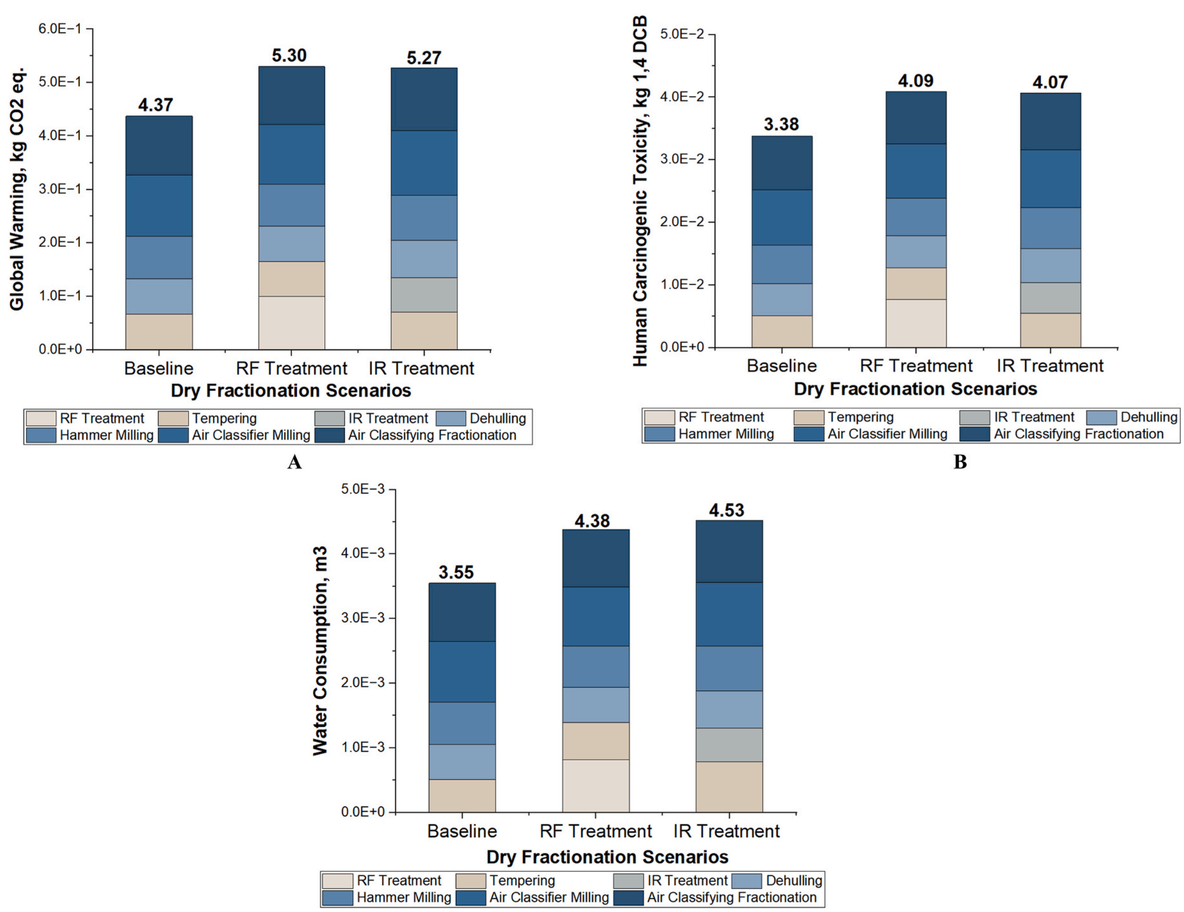


Fig. 6. Environmental impacts (midpoint) for dry fractionation scenarios showing process contribution: A) Global warming potential. B) Human Carcinogenic Toxicity; C) water consumption.

demand. In the case of water consumption, the IR treatment recorded highest due to the double stage tempering, thus before and after the pretreatment. Tempering is usually required prior to IR treatment to avoid excessive drying due to the high temperatures of up to 150 °C, that could be reached. With RF treatment, the aim was to maintain an initial moisture content of at least 12% but since the seeds used for these trials already contained about 13% moisture, furthertempering was not needed. All the midpoint factors recording very similar trends can be attributed to the electricity and water (for tempering) being the only process flow that goes into the study's system boundary; hence all impacts would be proportionally based on the measure of these utilities.

It is worth noting that, since the impacts are relative to the amount of protein concentrate produced, it considers the yields of the different process. This shows that the RF could have recorded a higher environmental impact if there were no increase in its yield (or a decrease) as compared to the Baseline, same applies to the IR Treatment. In the same way an increase in the yield, other than recorded, would have also decreased the environmental impact. To this end, similar to the economic performance, optimization towards increasing the yield for these pretreatment methods would go a long way in improving their environmental performances.

3.3.2. Process contribution (hotspot) analysis

From Fig. 6, the largest contributor to the midpoint factors was the air classifier milling, which contributed, across all the impacts categories, about 26% for the Baseline, 21% for the RF Treatment and 23% for the IR Treatment. The high impact is attributed to the two electrical motors driving the mill, thus the classifier wheel and one for the rotor, hence the large consumption of energy. This is followed by the air classification unit which contributes to about 25%, 21% and 22% to the overall impacts for the Baseline, RF Treatment, and IR Treatment scenarios, respectively. The air classification's comparative impacts associated with milling and air classification are consistent with previous studies on the dry fractionation, which shows that the milling unit(s) contribute more to environmental impacts than the air classification (Lie-Piang et al., 2021; Schutyser et al., 2015). The tempering sections for all scenarios contributed to 13.1%, 14.4% and 17.3% to Baseline, RF Treatment, and IR Treatment scenarios, respectively. The hammer milling and dehulling steps also contributed to an average (from the three scenarios) of 13% and 16%, respectively. For the pre-treatment methods, the RF contributed to about 19% of the overall impacts for the RF Treatment scenario with the IR treatment step contributing to about 12% of the overall impacts. For the dehulling process unit, the reduction in the impacts is attributed to the prior allocation of the impacts associated with the process to the hulls produced. Since the hulls are purchased as raw material to produce fibre-rich food products and animal feed, it would be unfair (to the protein concentrate) to move out of the system boundary without environmental burdens, and hence the proportional impacts were allocated to them. With regards to the pre-treatment, the results show that, although the pre-treatment steps add to the environmental impact, their contribution is averagely lower than expected.

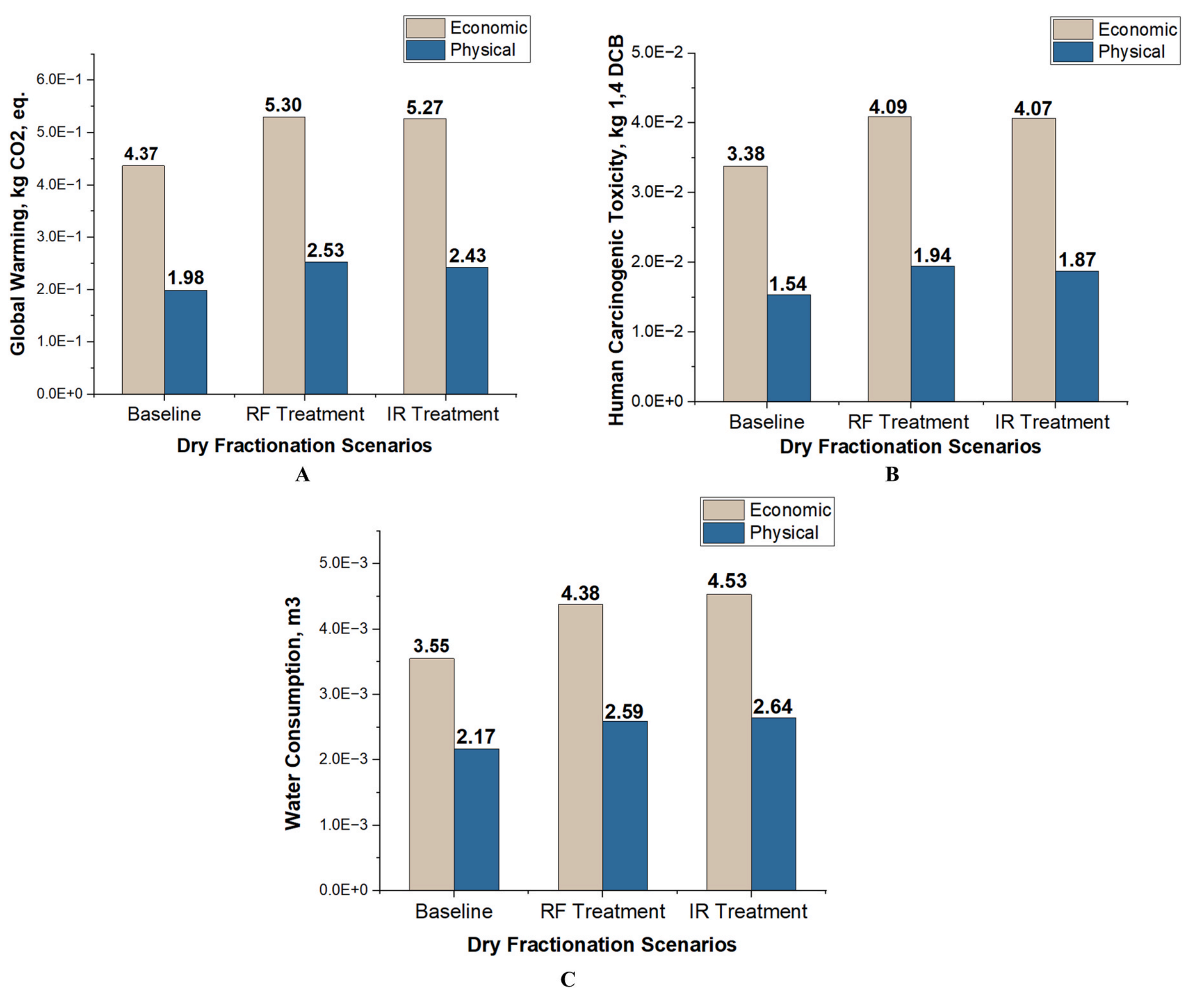


Fig. 7. Allocation sensitivity analysis (economic and physical) for the environmental impact categories: A) Global warming potential. B) Human Carcinogenic Toxicity; C) Water Consumption.

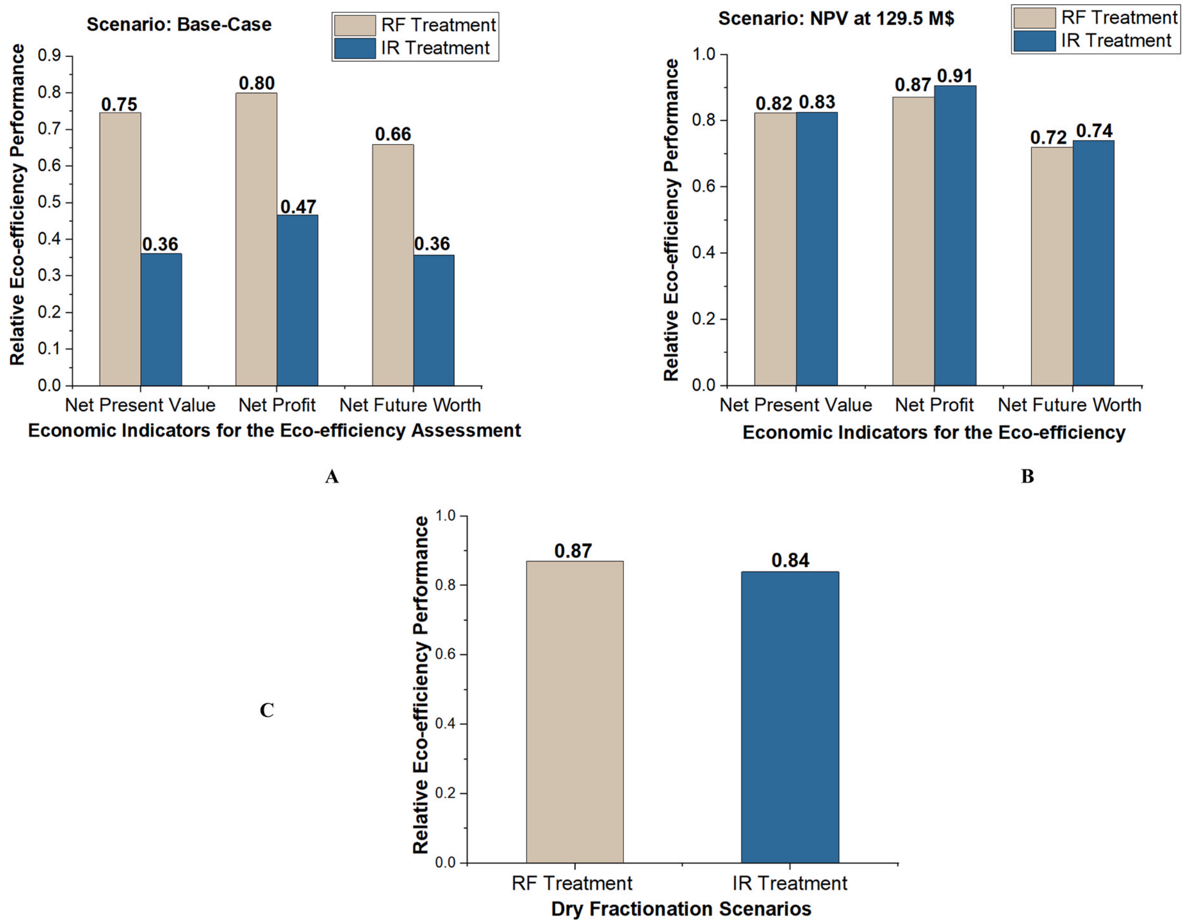


Fig. 8. Relative Ecoefficiency Performance (REE) for the RF Treatment and Micronization process scenarios. A &B: Economic based, C: Quality Indicator (Protein Purity).

3.3.3. Allocation sensitivity analysis

As mentioned in the methodology, economic allocation is employed for the multifunctional system, producing protein concentrates, starch-rich fractions, and hulls. This allocation method is selected because of the wide difference in the price of protein and the co-products for a better or fair assessment. The economic allocation method helps to avoid the allocation of large impacts to higher yield co-products with less value as compared to the major products (ISO, 2006). However, for a sensitivity analysis for this study, the physical (mass) allocation is also performed and compared to the base case (economic allocation) to highlight the impact of the methodological variation on the process scenarios' environmental performances. Allocation factors are based on the yields of the fine fraction and coarse fraction produced after fractionation. Fig. 7 shows the results of the allocation sensitivity analysis. There is very significant reduction across all impacts for all three scenarios from the graphs. For the mass allocation, we observe reductions of 54.8%, 52.3% and 54.0% for the Baseline, RF Treatment, and IR Treatment, respectively, across all scenarios for all environmental impacts. This is expected because the mass allocation factors were 0.198, 0.219, 0.192 for the Baseline, RF Treatment, and IR Treatment, respectively, derived from the yield of fine fractions. These factors increased to 0.410, 0.449 and 0.420 for Baseline, RF Treatment, and IR Treatment, for the economic allocation. The significant difference in the factors also results from the higher value of the protein concentrate as compared to the starch concentrate and hulls. One other advantage of the economic allocation is that it still incorporates the mass proportions of the different products, thus, the factors are derived are based on the total sales (product of mass and price) and not just the difference in prices. Although the economic allocation procedure is the better option for this case, some factors need to be finalized to nullify the effect of fluctuation of market prices for a longer period and ensure the results' reliability (Gadkari et al., 2021). This indicates that, it would be better to select the economic allocation procedure when consequential modelling (system expansion) cannot be performed, when carrying out an environmental impact assessment of pea protein concentrate production, to avoid allocating inaccurately large amounts of impacts to the co-products with a higher yield yet with lower economic value.

3.4. Eco-efficiency assessment

As mentioned earlier, the primary goal of industrial processors is to make economic gains. However, eco-efficiency allows processors to achieve this while minimally impacting the environment. This section therefore discusses the eco-efficiency performance levels of the dry fractionation scenarios.

3.4.1. Eco-efficiency indicators

Table 4 presents the eco-efficiency performance levels of the three dry fractionation processes for both economic-based and quality-based indicators. For the economic indicators, these are calculated under two economic scenarios. In the first scenario, which is the base-case scenario, the eco-efficiency performance levels were calculated using the NPV of the different fractionation processes, at a constant selling price of protein concentrate, 3.83 $/kg. In the second economic scenario, we assume that protein concentrates are sold at the MCSP at which the NPV is equal to that recorded by the Baseline process, 129.5 M $ ($MSCP_{129.5}$). At these NPVs, the eco-efficiency indicators are calculated for the two alternatives. A closer inspection of the table reveals that, the Baseline still outperformed the other two alternatives, recording the highest eco-efficiency values in all the indicators as well as both economic scenarios, with the IR Treatment performing least in all indicators. For product quality, the indicator used was based on the protein purity. Although there was a higher protein quality for the RF, the Baseline recorded the highest eco-efficiency of 1.37 kg protein per kg CO_2, with the IR Treatment recording the least, 1.15 kg protein per kg CO_2 while the RF Treatment recorded 1.19 protein per kg CO_2. This also implies that, the increase in the protein purity, in the case for the RF, is not able to offset the increase in environmental impacts.

3.5. Relative eco-efficiency (REE) – RF vs. IR

3.5.1. Economic-based REE

Fig. 8 presents the REE for the three case scenarios comparing the two alternative methods (RF Treatment and IR Treatment). Generally, it can be observed that the REE for the three case scenarios are all below one, suggesting that the two alternative fractionation pathways underperformed as compared to the Baseline. This is highly expected due to the highest economic performance and least environmental impact recorded by the Baseline fractionation as reported in the previous sections. However, comparing the two alternatives relative to the Baseline, across all indicators, it is evident that, the RF Treatment outperformed the IR Treatment significantly (more than 100% greater). This stems from the significantly lower economic performance of the IR Treatment process pathway (due to high capital costs of pretreatment unit) although it reported less environmental impacts as compared to the RF Treatment.

It is however interesting to observe that, for the scenario where the protein concentrate is sold at the $MSCP_{129.5}$, the IR Treatment process outperformed the RF Treatment process. The IR alternative recorded 0.83, 0.91, and 0.74 for NPV, Net Profit and Net Future Worth based ecoefficiency, respectively while the RF Treatment recorded 0.82, 0.87, and 0.72, for NPV, Net Profit, and NFW based-ecoefficiency, respectively. These results show that at much comparable economic performances, insignificant difference in environmental impacts can strongly impact the eco-efficiency performance of process alternatives.

Table 4
Eco-efficiency performance for dry fractionation scenarios.

Value Indicators (Economic & Product Quality)	Units	Fractionation Scenarios		
		Baseline	RF Treatment	IR Treatment
Base-Case Scenario (Constant price for processes)				
Net Present Value	MM$ per kg CO_2 eq	296.3	221.3	107.2
Net Future Worth	MM$ per kg CO_2 eq	597.7	464.2	251.1
Net Profit	MM$ per kg CO_2 eq.	2.37	1.89	1.10
MSCP Scenario (RF and IR using 4.08 and 5.56 $/kg, respectively)				
NPV	MM$ per kg CO_2 eq	296.3	244.3	245.7
Net Future Worth	MM$ per kg CO_2 eq	597.7	508.1	521.1
Net Profit	MM$ per kg CO_2 eq	2.37	2.06	2.15
Quality indicator				
Protein Purity	kg protein per kg CO_2 eq	1.37	1.19	1.15

3.5.2. Quality-based REE

Eco-efficiency can also be measured by the product value in terms of the added quality. In this study, as shown in Fig. 8C, the protein purity is used as the quality metric for the analysis. The RF Treatment recorded a higher REE of 0.87 as compared to 0.84 recorded by the IR Treatment. This result is also expected as the protein concentrates produced from these fractionation scenarios had purities of 63.1% and 60.8% respectively. The estimated values are not equal to or does not exceed one (1), even though higher purity was recorded for the RF treatment pathway. Again, this occurrence is attributed to the significantly lower environmental impacts recorded by the Baseline process. However, this presupposes that, although there was a very significant difference in the economic-based eco-efficiency (Fig. 8A) between the pre-treatment alternatives, the eco-efficiency based on the increase in the concentrate's quality (purity) did not show a very significant disparity, thus they recorded comparable values (Fig. 8C). This predicates the significance of incorporating quality of food products in their eco-efficiency assessment to allow for a more holistic and plenary performance assessment approach.

3.6. Competitive advantage, risk, and trade-off analysis

Overall, the results have shown that, the Baseline performs best in terms of high economic returns and least environmental affect, primarily attributed to absence of added equipment costs and operating energy, consecutively recording the highest eco-efficiency. However, from the consumer perspective, protein purity, techno-functional and nutritional quality as well as product safety aside other social and socio-economic factors, would be the major priorities regarding the purchase of protein concentrate. This would cause a competitive advantage of the protein products produced by the pre-treatment methods over the untreated (Baseline) process pathway. This means that if there is an added mark-up in the selling price of the thermal-treated proteins compared to the untreated usually improved safety, flavor, etc. that would significantly increase the revenues.

Now juxtaposing the two pre-treatment alternatives, with a constant selling price (same as the baseline, 3.83 $/kg), the RF Treatment option outperforms the IR Treatment option in terms of the relative eco-efficiency to the baseline. On the other hand, the adoption of the IR Treatment process, if the protein concentrates are sold at 4.08 $/kg (the MCSP with same NPV as baseline), would result to a higher eco-efficiency performance than the RF Treatment as seen in Fig. 8b. However, the possible trade-offs or risks associated, is that the less $MCSP_{129.5}$ for the RF Treatment, 4.08 $/kg also offers a competitive advantage over the IR Treatment with 5.56 $/kg due to socio-economic factors considered by consumers, which can influence its adoption by industrial processors. This competitive advantage could result in lower sales for the micronized or IR treated material, and subsequently into lower revenues which could serve as a hindrance in achieving the economic value as projected. From these existing trade-offs, the industrial processors could price their products based on the technologies adopted and quality of product, taking into consideration what to gain and what to compromise.

4. Strengths and limitations of study

This study is the first of its kind that applies eco-efficiency methods in assessing the holistic sustainability of pea protein extraction, looking at the technical, economic, and environmental issues. Also, since the analyses were based on a pilot-scale production process, application of these results for decision making at the industrial level is highly feasible with a much lower level of uncertainty, as compared to a laboratory scale analysis. However, the inclusion of the techno-functional properties as part of the quality assessment, which was not considered per the aim of this study, might make one product more attractive and can alter the dynamics since all the processes are showing good economic returns.

Therefore, further studies could be conducted based on processing units and conditions employed in the fractionation processes to assess the possible techno-functional properties of the concentrates to support the findings from this study and re-assess their comparison, based on the addition of a new criterion, product functionality.

5. Conclusions

The present study assesses the sustainability of dry fractionation of pea protein using different pre-treatment methods as compared to a baseline method without an upstream pre-treatment step. The two-pre-treatment methods used were the RF treatment and IR treatment, both dry thermal processing methods. From the technical perspective, the scenario with RF pre-treatment methods, outperformed the baseline and the IR pre-treatment scenarios, recording highest protein separation efficiency, which is as result of the high-depth penetrability of the RF radiation that can enhance the disruption and disentanglement of the protein-starch matrix in the cotyledon. For the economic performance, the baseline scenario outperformed the other two scenarios. This is attributed to the less operation units required by this process as compared to the pre-treatment scenarios and hence there were less cost in terms of both capital and operating expenses.

Regarding the environmental dimension, the Baseline outperformed IR and RF Treatment methods (the least performing). Allocation sensitivity performed showed a significant reduction in environmental impacts with physical (mass) allocation compared to the economic allocation for all impact indicators, across all three fractionation scenarios. The overall performance was carried out using the eco-efficiency assessment tool. Although, alternative processes (with pre-treatment methods), performed relatively lower than the baseline process in terms of their eco-efficiency levels, they can be sold at higher prices to achieve the same economic gains in terms of the NPV due to the high quality of the product in terms of purity, nutritional quality, reduced anti-nutritional factors, organoleptic properties, safety, amongst others.

To the best of our knowledge, this is the first study of its kind to apply an eco-efficiency assessment tool, specifically incorporating the protein purity, in assessing the techno-eco-environmental performance of the pea protein extraction process. For this present study, dry fractionation of pea protein was carried using different pre-treatment methods. Findings from this analysis shows the interplay among the process, economic and environmental dynamics for the three scenarios. Also, the primary data obtained from the pilot scale production as well as data on the economic and environmental impact obtained from the subsequent sustainability analyses can be used in other studies to carry out LCA and TEA of similar fractionation processes. Moreover, they can be compared with other new or modified fractionation processes. Most importantly, this study presents the advantage, risks and trade-offs associated with the adoption of any of the three fractionation processes. This information would guide industrial pea protein processors in decision-making regarding selecting the "optimum" processing pathway. The industries could also adopt the minimum selling prices for product pricing of the protein concentrates. Finally, this study would set the path for subsequent techno-eco-environmental studies for other dry fractionation processes, the wet fractionation as well as the hybrid fractionation process. This would go a long way in selecting sustainable pathways for pea protein production at the industrial scale.

CRediT authorship contribution statement

Derrick K. Allotey: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Ebenezer M. Kwofie:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Conceptualization. **Peter Adewale:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Anusha G.P. Samaranayaka:** Writing – review & editing, Resources, Methodology, Investigation, Formal analysis. **Nandhakishore Rajagopalan:** Writing – review & editing, Resources, Investigation. **Praiya Asavajaru:** Resources, Investigation. **Darrin Klassen:** Resources, Investigation. **Michael Ngadi:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

I have a link attached to the Supplementary Data

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.142298.

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