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A Multicriteria Decision Framework for the Selection of Biomass Separation Equipment

For the first time, a two-stage decision support framework for equipment selection, applied to biomass separation, is presented. In the first stage, the framework evaluates from a number of equipment based on the process requirements and outputs only those that offer a technically feasible separation. In the second stage, the analytic hierarchy process is applied for performing a multicriteria decision analysis to select amongst the feasible equipment based on separation performance and energy consumption criteria. This approach systematically considers the relative importance of those different alternatives and selection criteria by pairwise comparisons. The output of the framework is an overall ranking of equipment as well as a sensitivity analysis of the results for different weighting of the criteria. These results can be used to equip practitioners in the field of bioseparations with a tool for making more consistent and better-informed equipment selection decisions.

Keywords: Analytic hierarchy process, Biomass separation, Equipment selection, Multicriteria decision analysis

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1 Introduction

Bioseparations play an essential role in a wide range of industrial applications in the pharmaceutical and biopharmaceutical, food and beverage, wastewater treatment, and chemicals and fuels sectors [1, 2]. Examples of biologically derived products from these industrial applications are antibiotics, vaccines, yoghurt, citric acid, solvents, and vitamins. This diversity of industrial applications has led to the development of a variety of techniques and unit operations for efficient processing of biological materials. This is because bioseparations are not only technically challenging but also economically expensive in many cases. Depending on the type of biological products, the bioseparation cost can be a substantial component of the total cost of bioprocessing, ranging from 15 % to 80 % [1].

Each bioseparation process must be adapted to separate, purify, or recover the desired bioproduct. Fig. 1 illustrates the general steps and operations in bioseparation that may be involved in a bioproduct recovery process [3]. The main concerns in the primary recovery stages include separating the products from cells or cell debris and removing the impurities. Biomass separation, cell harvesting, cell disruption, cell debris removal, and product extraction are different types of processes in the primary recovery stages. In the intermediate recovery stages, the product is concentrated, which can be achieved through a variety of methods. The final purification stages focus on achieving the required purity of the product using a final purification, dehydration, or solvent removal.

Different unit operations need to be selected to achieve the desired recovery in bioseparation processes. The associated equipment will differ in its mechanical design and operating principles. For instance, in the biomass separation process, it might be possible to select amongst unit operations such as filtration, centrifugation, and microflotation for the primary recovery stage. Similarly, for the concentration required in the intermediate recovery stage, the options might include evaporation, crystallization, and adsorption. In the final purification stages, chromatography, diafiltration, and electrodialysis are amongst the unit operations that might be selected to purify the final product.

The selection of equipment for the aforementioned unit operations is a complex task that requires the consideration of multiple criteria, which have different units of measurement and scales. The complexity of the task is further increased due to a variety of feasible alternatives and the conflicting objectives for selecting equipment under constrained operating conditions and process requirements [4]. Equipment selection is also an important task that affects process efficiency. Selecting not only the right but also the optimal equipment will have implications in terms of product quality, production rate, and use of resources.

Most separation methods for biomass deal with solid-liquid separation processes. The selection of a biomass separation

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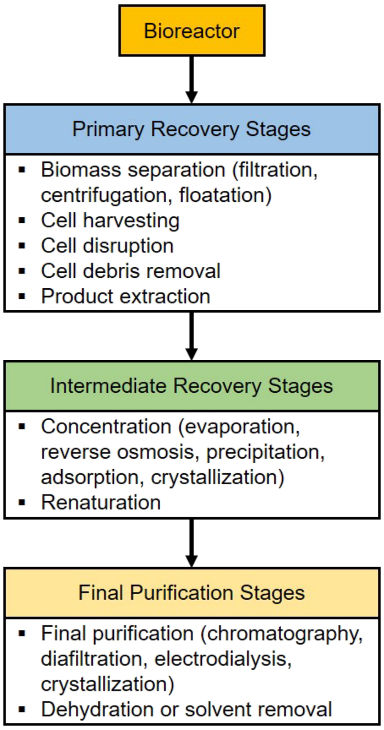

Figure 1. General steps and operations involved in a bioproduct recovery process as adapted from Harrison [3].

technique and the required equipment will depend on process requirements and a number of criteria that are often complex and difficult to quantify. A number of different equipment selection schemes for solid-liquid separations have been proposed in the literature [5–7]. Lahdenperä et al. [5] developed a small rule-based expert system to select a solid-liquid separation method. The knowledge database was built on extensive literature survey and an inference engine was built to search for solutions to a given problem using knowledge stored in the database. The work was mainly concerned with functional constraints set by the process. In this expert system, the suitability of equipment for a specific task is defined by operating ranges of different parameters such as particle size, settling velocity, feed concentration, cake formation- and final state of solids, whereas rules are implemented in the form of 'if-then' logic sequence for each piece of equipment. However, separation performance and utility costs were not considered in the expert system.

Wakeman [6] introduced a more formalized procedure for solid-liquid separation equipment selection using a step-by-step approach. The procedure considers the process requirements to rule out any unsuitable equipment and provides a shortlist of equipment potentially suitable for an application. The procedure was further extended in Tarleton and Wakeman [7] and separation performance was also considered for each different unit operation. However, utility costs in terms of energy consumption and separation performance such as capacity factor were not considered in the framework.

The present paper proposes a systematic decision analysis framework to support the selection of equipment for biomass separation considering multiple criteria and subcriteria, including separation performance and energy consumption. Chakraborty and Banik [4] suggested that an 'effective and efficient multicriteria decision-making tool' should be used to address equipment selection problems. This is because an equipment selection problem is found to be unstructured, characterized by many feasible alternatives and conflicting criteria, as well as requiring extensive domain-dependent knowledge. The multicriteria decision analysis (MCDA) method allows the combination of multiple criteria to assess alternatives and offers a systematic way to structure a decision problem [8–11]. This method has been researched intensively [12] and used successfully in many applications such as engineering [13–15], environmental science [16], energy and supply management [17], and equipment selection [18, 19].

However, despite the advancement of MCDA, there is no study in the literature demonstrating its application to biomass separation equipment selection. Hence, the aim of this work is to develop a framework based on MCDA to support decision-makers on the selection of biomass separation equipment, so that the decisions are more consistent and better-informed. The novelty of the present work is on combining the evaluation of a number of equipment based on the process requirements, in a first stage, to output only those that offer a technically feasible separation, followed by the use of an MCDA technique, as a second stage, to select amongst the feasible equipment based on separation performance and energy consumption criteria. The framework is adapted from the recently developed methodology for sustainable chemical process routes selection [20] and combined with process requirements screening on solid-liquid separation [7].

In this paper, the work focuses on equipment selection for biomass separation process in the primary recovery stages of bioseparation. This is the starting point to introduce the framework, with the possibility to extend the application to other processes. There are two main groups of solid-liquid separation in the primary recovery stages: sedimentation and filtration [21], which are the main alternatives considered in this paper. An illustrative example is presented on selecting biomass separation equipment in those two groups under specific operating conditions and process requirements to demonstrate the applicability of the framework.

2 Methodology

The methodology employed for the equipment selection of biomass separation used in this study is displayed in a diagram in Fig. 2. The overall process consists of three main steps: (i) identification of alternatives, performed in stage one; (ii) assessment of feasible alternatives, and (iii) integration of assessment by the MCDA method, which are performed in stage two.

2.1 Step 1: Identification of Alternatives

At this step, the biomass process and product is characterized, in terms of feed solid properties, washing requirement, inlet

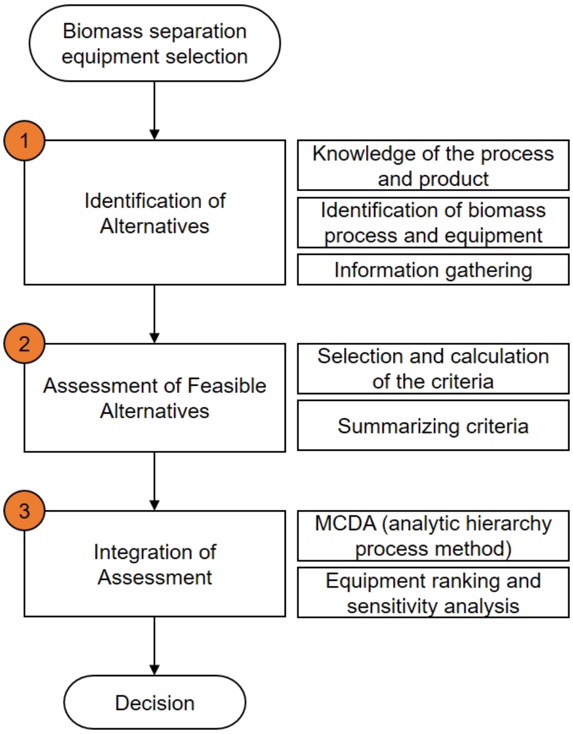

Figure 2. Proposed methodology for biomass separation equipment selection.

flow range, continuous or batch operation, clarity, and the objective of the separation process. An initial list of equipment as the alternatives is determined at this step that can come from decision-makers or experts under the specific condition required for the process. Based on this information, the equipment is classified and evaluated further.

The aim of this step is to specify the general requirements of the separation process environment in terms of duty specification and to state the performance of the sedimentation and filtration units. An initial duty specification can be classified based on the scale of the process, the operation mode, and the overall objective of the separation process [7], as indicated in Fig. 3 a. A specific characteristic letter is used to identify each specification, so that a group of letters defines the nature of the general requirements. For instance, a small-scale (c) continuous operation (e) for washed solids (h) would be coded as *ceh*. The specification for sedimentation performance is determined by the initial settling rate, the clarity of the supernatant liquid, and the final proportion of sludge that is also coded with a specific characteristic letter as shown in Fig. 3 b. For instance, a slurry that settles at 0.08 cm s^{-1} (A) to yield a clear liquid (E) and a 1 % proportion of sludge (F) would be coded as *AEF*. The specification for filtration performance is determined by the average rate at which cake is formed [7] and coded with a specific characteristic letter as demonstrated in Fig. 3 c. For instance, a slurry that forms a cake at the rate 2 cm $\min^{-1}$ is coded L.

2.2 Step 2: Assessment of Feasible Alternatives

In step 2, the performance of each equipment is assessed based on the chosen criteria. In this study, the criteria selected are separation performance and energy consumption, which are derived from the literature. The separation performance criterion is represented by five subcriteria: dryness of the solid product, effectiveness of solid washing, quality of the liquid product, tendency of the equipment to cause crystal breakage, and capacity factor. The evaluation of the first four subcriteria is based on the information and experimental results from [7], whereas the last subcriterion is estimated based on the recent experimental results from [22]. It is necessary to describe that the capacity factor (Σ)[1] is an indication of separation performance of an equipment compared to a continuous gravity settling tank, which relates the volumetric flow rate (Q) to the gravity settling velocity (v_g) as described in Eq. (1). The energy consumption criterion is represented by the specific settling energy consumption that is derived by recent experimental results from [22] by use of an energy consumption chart.

$$Q = 2v_g\Sigma \tag{1}$$

It is essential to note that the list of criteria can be constructed by an extensive literature combined with experts and decision-makers' knowledge through brainstorming, semistructured questionnaires, and discussion. The criteria listed in this study can be further modified for each specific case study. For instance, other criteria such as capacity, concentrating power, yield, equipment and material cost can also be considered under specific requirements. Nonetheless, the listed criteria used in this paper should serve as a starting point for the equipment selection assessment of biomass separation.

2.3 Step 3: Integration of Assessment

At this step, criteria are combined systematically to achieve an integrated equipment selection assessment through an MCDA method. MCDA methods are based on preference measurement in which preferences are stated by decision-makers with respect to criteria and alternatives. The aim is to obtain weights and priority value for each alternative. The best alternative is the one with the highest priority value with respect to the decision-makers' preferences. Many MCDA methods are available that can be used to analyze a specific decision-making problem. Decision-makers should know the problem structure, the required modeling effort, and input information to select one of the MCDA methods. Description of different MCDA methods can be found in [8, 11, 23].

The analytic hierarchy process (AHP) is one the MCDA methods for a systematic decision-making process. AHP has received substantial academic and practitioner interest [24] and has been applied successfully in a wide range of applications such as petrochemical processing [25], in the chemical

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[1] List of symbols at the end of the paper.

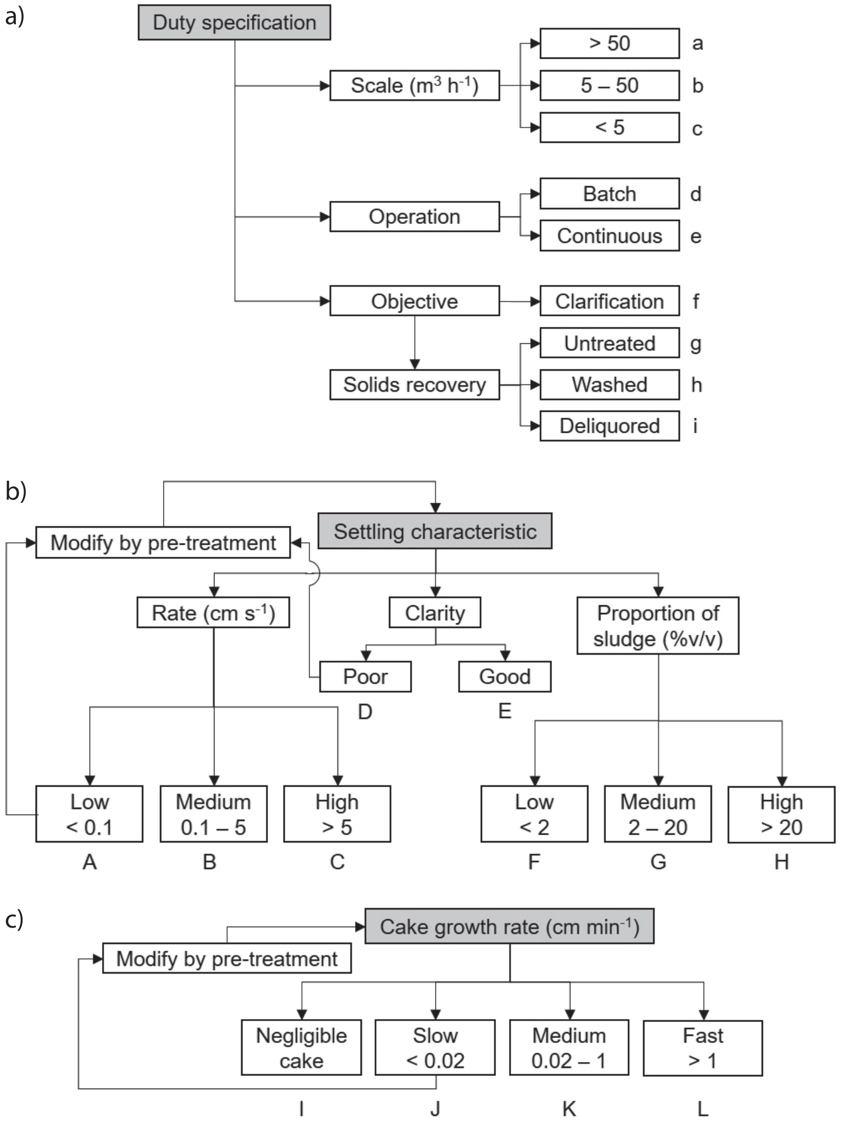

Figure 3. Initial screening for the feasible biomass separation equipment selection based on the process requirements specification: (a) coding the duty specification; (b) coding the slurry sedimentation characteristic; (c) coding the slurry filtration characteristic [7].

process industry [20, 26], and in equipment selection [16, 19]. AHP was first developed by Saaty [27] to perform decision trade-off between multiple criteria in a hierarchically organized structure. It can be applied to complex problems, because it breaks them down into subproblems according to this hierarchical structure. Another advantage is that the AHP method accepts any criterion for inclusion and allows individual decisions to be aggregated into overall criteria, which allows other members to review and participate in that aspect of the decision-making process at an appropriate level of detail. Moreover, AHP is capable of evaluating quantitative as well as qualitative criteria and alternatives on the same preference scale by using pairwise comparisons between criteria and alternatives, which eliminates a requirement for a prior definition of a preference function [23].

The AHP is generally composed of four steps: constructing a hierarchical structure, establishing a judgement matrix, consistency check, and sensitivity analysis.

- Constructing a hierarchical structure: The problem is decomposed into several important considerations and the hierarchical structure is constructed into different levels. The first level is the decision goal. The criteria to be considered in the decision-making are on the second level that can be expanded into lower levels if subcriteria are considered. The lowest level consists of all the alternatives to be evaluated in the decision-making. The number of such alternatives should be limited to nine as suggested by Saaty [28]. There are three main problems if there are more than nine alternatives: it is time-consuming to carry out pairwise comparisons; with a large set of comparisons, it can be difficult to ensure consistency; and there is a risk of only small differences in the final score. However, AHP can be used to rank larger sets of alternatives by splitting the set into consecutive clusters and ranking alternatives within clusters [29].
- Establishing a judgement matrix: The relative importance of each criterion and subcriterion is evaluated through pairwise comparisons to establish a judgement matrix. Afterwards, weights are calculated by the eigenvalue method to determine the overall ranking of alternatives. Different judgement scales in AHP have been used in the literature [24] apart from the original linear scale proposed by Saaty [27]. Saaty [30, 31] advocates the linear scale as the best scale to represent judgement scale. Moreover, the linear scale offers a balance between consistency and allocation of priority [32]. Hence, the original linear scale is used for pairwise comparison in this study as indicated in Tab. 1.

The basis for assigning the number during pairwise comparison can be either subjective based on decision-makers' and/or experts' knowledge and experience or objective based on quantitative measures that are linked to the criteria. Responses are gathered in verbal form and subsequently codified on a nine-point scale as described in Tab. 1. For example, if the first criterion is very strongly more important than the second criterion, the first-second criteria comparison will contain the value 7 as shown in Tab. 1. Scales 2, 4, 6, and 8 are intermediate values that can be used to represent shades of judgement between the five basic assessments. If the judgement is that the second criterion is felt to be very strongly more important than the first criterion, then the reciprocal index value is assigned which in this case the value 1/7 would be assigned as displayed in Tab. 1.

Table 1. AHP linear judgement scales for pairwise comparison used in this study.

Judgement value	Definition	Explanation
1	Equal importance	Two decision elements (i.e., criteria) contribute equally to the parent decision element (i.e., goal).
3	Moderate importance	Experience and judgement slightly favor one decision element over another.
5	Strong importance	Experience and judgement strongly favor one decision element over another.
7	Very strong importance	Experience and judgement very strongly favor one decision element over another.
9	Extreme importance	Experience and judgement extremely favor one decision element over another.
2, 4, 6, 8	Intermediate value of the adjacent judgment	Judgement value between equal, moderate, strong, very strong, and extreme.
Reciprocal	The judgement value corresponds to reverse relationship	If *v* is the judgement value when *i* is compared to *j*, then *1*/*v* is the judgement value when *j* is compared to *i*.

- Consistency check: The inconsistency and intransitivity of judgements and preferences may lead to perturbations in the eigenvector calculation. Hence, consistency during pairwise comparisons is checked through a consistency ratio, *CR*, i.e., the ratio of consistency index, *CI*, to an average random consistency index, *RI*, as described in Eq. (2) [33].

$$CR = CI/RI \tag{2}$$

The random consistency index, *RI*, is derived from a randomly generated reciprocal matrix of order *n* with 500 sample sizes using the scale 1/9, 1/8, …., 1, …, 8, 9 as indicated in Tab. 2 for *RI* of the order 1 to 10 matrices. The consistency index, *CI*, is given by Eq. (3) and can be calculated directly from the judgement matrix.

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{3}$$

where $\lambda_{\max}$ is the largest eigenvalue of the judgement matrix and *n* is the order of the matrix. Saaty [33] recommended to study again the problem and revise the judgement if the consistency ratio *CR* is more than 0.1.

- Sensitivity analysis: Weights are varied to assess the impact on the results and to answer the 'what-if' question that decision-makers may have. The results of this sensitivity analysis can be used as part of the decision to be taken to determine if a given criterion can be compromised at the expense of another criterion that affects the overall ranking of alternatives.

3 Illustrative Example

The framework described in this paper is illustrated through an example for selecting optimally a biomass separation equipment. Even though it is applied for a certain biomass product, the framework presented here is structured so it can be applied for various biomass products with different processes. It also can be adapted to different process complexity, including physical properties such as viscosity, solid and liquid densities, and filter resistance, as well as additional criteria in decision-making such as capital and operational expenditures.

3.1 Identification of Alternatives

The goal in this illustrative example is to select optimally either a sedimentation or filtration unit operation to process a biomass product **X**. The feed consists of particles of size 10 μm and at a solids concentration of 2 % by mass. The required operating conditions are: inlet flow rate range from 2 to 2000 m^3h^{-1}, continuous operations, settling rate between 0.1 and 5 cm s^{-1}. The objective of the separation process is clarification, between 2 and 20 % v/v of proportion of sludge, and the recovered solids do not require washing nor deliquoring.

This study evaluates the following biomass separation equipment to process the biomass product [34], as illustrated in Fig. 4.

(a) Hydrocyclone (conical reverse-flow): the equipment has no moving parts and consists of an inverted conical bottom section attached to a cylindrical section that includes a tangential inlet, through which the feed is injected. Coarser particles exit as a suspension in the underflow stream at the bottom and the finer fractions leave through the cylin-

Table 2. Random consistency index values derived from a randomly generated reciprocal matrix of order *n* with 500 sample sizes using the linear scale.

Order of matrix *n*	1	2	3	4	5	6	7	8	9	10
Random consistency index *RI*	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

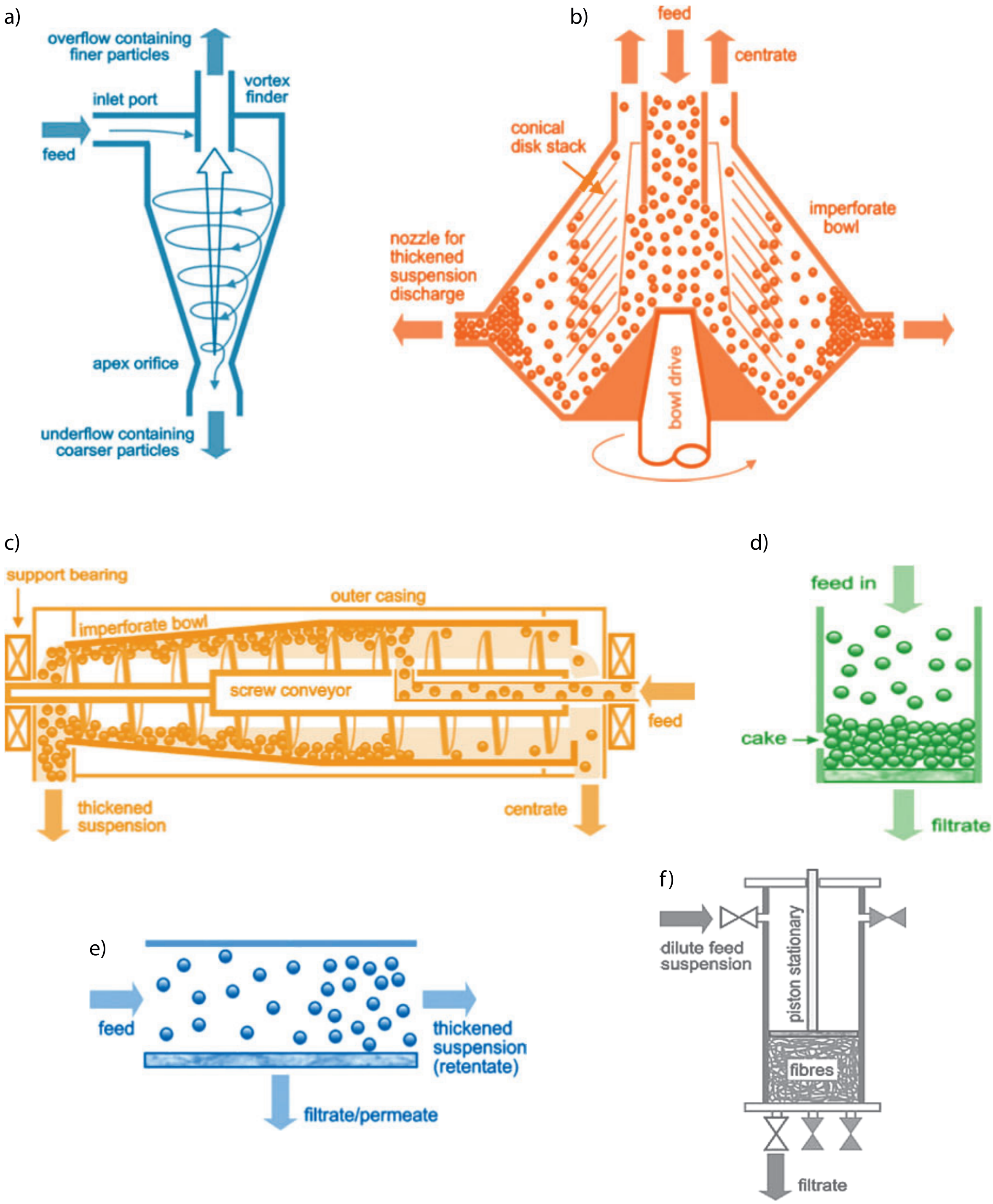

Figure 4. Considered alternatives of equipment for biomass separation: (a) hydrocyclone (conical reverse-flow); (b) disc stack centrifuge; (c) scroll decanter centrifuge; (d) dead-end membrane filter; (e) low-shear crossflow ultrafilter; (f) deep-bed (fiber) filter (modified after [34]).

drical vortex finder at the top via the combination of centrifugal forces and swirling motion.

(b) Disc stack centrifuge: solids are fed centrally from the top then travel through the annular spaces between the discs that are spun on a common vertical axis. Particles are accumulated on the under side of the discs, as a result of centrifugal forces, then they slide down towards the outer periphery of the centrifugal bowl, whereas the clean liquid phase flows through the outlet at the top.

(c) Scroll decanter centrifuge: the solids feed enters through the central axis of the centrifuge and is conveyed cocurrently along the walls of the bowl by a helical screw and moved through the narrower conical end of the centrifuge by inertial forces to the discharge. The clean liquid phase leaves the centrifuge through a port at the broader end of the bowl.

(d) Dead-end membrane filter: with applied pressure, filtration takes place either on the surface and internally through the depth of the microporous membrane, normally constructed symmetrically, or at the top of the track-etched membrane pores in a sieve-like manner.

(e) Low-shear crossflow ultrafilter: the feed is pumped at a constant pressure and rate into a module (or modules) and caused to flow tangential to the stationary semipermeable membrane surface(s). The turbulent crossflowing stream generates shear forces at the membrane and the filtrate is collected, whereas the thickened suspension is recirculated until the desired solids concentration is achieved.

(f) Deep-bed (fiber) filter: the dilute feed suspension is compressed by a hydraulically operated piston against thick fibers in which the feed is exposed to a combination of diffusional, gravitational, and/or hydrodynamic forces, as it passes through the fibers. The fibers are cleaned by releasing the piston pressure upwards and backwashed with filtrate to expand the bed.

Tab. 3 summarizes the classification of each equipment based on the suitability for the process in terms of duty specification and the slurry separation characteristics. The information in Tab. 3 is gathered from the literature [7] and can be updated based on new experimental data, experts‘ knowledge, further testing, and/or specific technical documents.

Table 3. Classification of biomass separation equipment evaluated in this paper based on the suitability for duty and slurry separation characteristics.

Type of equipment	Duty specification	Separation characteristics	
		Settling	Filtering
Hydrocyclone (conical reverse-flow)	a or b	B or C	
	e	D or E	
	f, g, or h	F or G	
Disc stack centrifuge	a, b, or c	A or B	
	d or e	D or E	
	f or g	F or G	
Scroll decanter centrifuge	a, b, or c	(A), B, or C	
	e	(D) or E	
	f, g, (h) or (i)	F, G, or H	
Dead-end membrane filter	b or c	A or B	I
	d or e	D or E	
	f	F	
Low-shear crossflow ultrafilter	b or c	A or B	I
	d or e	D or E	
	f, g, or (h)	F	
Deep-bed (fiber) filter	b or c	A	I
	d or e	D or E	
	f	F	

( ) around a letter index indicates a marginal choice.

3.2 Assessment of Feasible Alternatives

Not all the biomass separation equipment options will perform with the same degree of effectiveness. Hence, a set of criteria is required to evaluate the equipment to be selected. As mentioned in Sect. 2.2, the criteria and subcriteria selected in this study to assess the alternatives are separation performance, i.e., solid product dryness, washing requirement, liquid product quality, crystal breakage, and capacity factor, as well as energy consumption.

The relative performance indices used in [7] are adapted to evaluate the first four subcriteria for separation performance as described in Tab. 4. Each equipment is allocated a relative performance index between 0 and 9, with larger number indicating better performance.

Tab. 4 also shows the state of discharged solids product as a slurry or a cake, and the required feed solids properties for each equipment. The information in Tab. 4 is useful for an initial assessment of equipment with regards to the required feed solids properties a unit operation can handle. For instance, all the sedimentation unit operations, i.e., hydrocyclone, disc stack and scroll decanter centrifuges, fulfil the process requirements, whereas all the filtration unit operations, i.e., dead-end membrane filter, low-shear crossflow ultrafilter, and deep-bed fiber filter, fail to meet one of the required feed solids properties and can be ruled out for further evaluation. This initial equipment elimination in the first stage of the methodology is important to guide the decision-maker on evaluating feasible equipment based on the requirements of the desired biomass process.

The capacity factor subcriterion and energy consumption criterion are evaluated based on published experimental results [22] for all sedimentation unit operations evaluated in this study. Fig. 5 presents the performance chart for all the sedimentation unit operations considered, which can be used to calculate the capacity factor of each equipment.

Fig. 6 displays the specific settling energy consumption chart for each equipment being evaluated. The data from charts in Figs. 5 and 6 was compiled for each equipment and is summarized in Tab. 5. It is important to note that these charts and the table are for a specific type of the corresponding equipment, e.g., a particular size or model. For instance, the capacity factor for the disc stack presented in Tab. 5 is for a mid-size machine; data for a larger-size equipment with a larger capacity factor might be found from the different manufacturers.

As described by Eq. (1) in Sect. 2.2, a larger capacity factor indicates a better separation performance since it will result in a lower settling velocity needed for a given flow rate. The settling velocity under gravitational acceleration v_g (not under centrifugal acceleration) is calculated using Stokes' law as described in Eq. (4):

Table 4. Relative performance characteristics of biomass separation equipment evaluated in this paper.

Type of equipment	Performance indices				Feed solid properties	
	Solid product dryness and state[1)]	Washing	Liquid product quality	Crystal breakage	Particle size [µm]	% by mass solid in feed
Hydrocyclone (conical reverse-flow)	1 S	2	4	7	5–200	2–40
Disc-stack centrifuge	2 S	–	–	6	0.1–100	0.05–2
Scroll decanter centrifuge	4 C	3	4	3	1–5000	4–40
Dead-end membrane filter	N	–	9	8	0.1–10	< 1
Low-shear crossflow ultrafilter	1 S	2	9	–	0.00 –0.05	< 20
Deep-bed (fiber) filter	N	–	8	–	0.1–40	< 1

Performance index '–' may be taken to mean either zero, i.e., that the equipment is not effective, or the equipment is not suitable for that duty; [1)]state of solids product: S = slurry or free flowing, C = cake, N = solids are not generally recoverable.

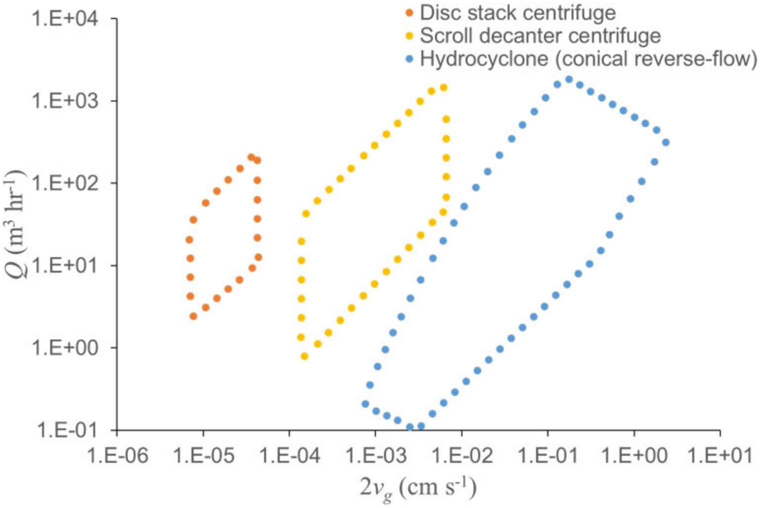

Figure 5. Performance chart of sedimentation unit operations for calculation of capacity factor criterion, modified after [22].

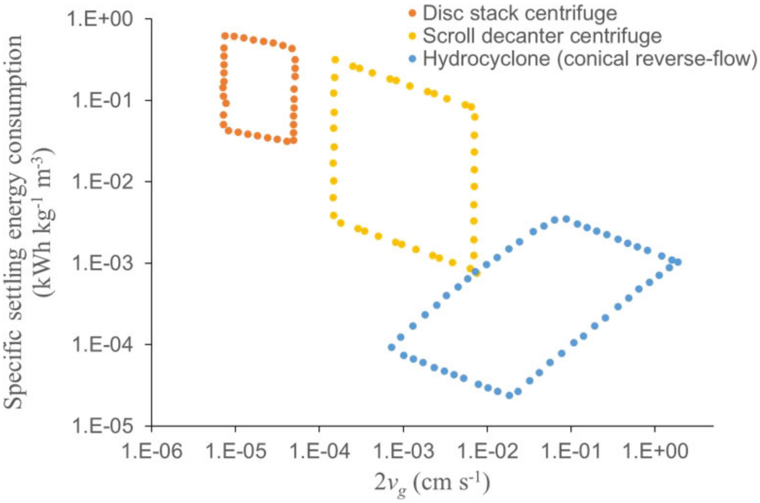

Figure 6. Specific energy consumption of sedimentation unit operations for sedimentation of a single particle unit volume of feed flow and particle mass, modified after [22].

$$v_g = \frac{\Delta\rho d^2 g}{18\mu} \tag{4}$$

where d is the particle cut-size diameter, i.e., the size at which particles have a 50 % chance of passing through the outlets of the separator, $\Delta\rho$ is the density difference between phases, g is the gravitational acceleration, and μ is the dynamic fluid viscosity. The characteristic of the system is defined as the ratio of volume flow rate to capacity factor Q/Σ, which is twice the settling velocity of particles at the particle cut-size under gravitational acceleration as described in Eq. (1). The diameter of a particle that is settling in a separator can be found by using Stokes' settling velocity defined in Eq. (4) if the properties of the particle and fluid are known. Higher values for Q/Σ indicate that larger particles will be separated in a centrifuge as a result of either a smaller capacity factor or a higher volume flow rate.

According to the information in Tabs. 4 and 5, there is no biomass separation equipment for product **X** that is optimal for all criteria/subcriteria. For instance, from Tab. 4, the scroll decanter centrifuge is the best option in terms of solid product dryness and washing criteria but the worst in terms of crystal breakage. On the other hand, the hydrocyclone has the best crystal breakage and energy consumption characteristics, but is relatively poor in terms of washing and also the worst for solid product dryness and capacity factor. Similarly, from Tab. 5, the disc stack centrifuge is the best option in terms of capacity factor related to the separation performance criterion but the worst in terms of the energy consumption criterion. A compromise between criteria and subcriteria should therefore be reached in order to make a decision. MCDA can be used at this stage to identify the optimum option by including the experts' knowledge and carrying out a systematic assessment.

Table 5. Separation performance and energy consumption criteria for all of the feasible unit operations.

Type of equipment	Separation performance			Energy consumption	
	Settling velocity [$\mathrm{cm\,s^{-1}}$]	Flow rate [$\mathrm{m^3h^{-1}}$]	Capacity factor [$\mathrm{m^2}$]	Settling velocity [$\mathrm{cm\,s^{-1}}$]	Specific settling energy consumption [$\mathrm{kWh\,kg^{-1}m^{-3}}$]
Hydrocyclone (conical reverse-flow)	7.5×10^{-4}–2.3	0.1–1.9×10^{3}	0.94–3.5×10^{2} (63.9)	7.2×10^{-4}–1.9	2.4×10^{-5}–3.5×10^{-3} (8.6×10^{-4})
Disc stack centrifuge	6.8×10^{-6}–4.3×10^{-5}	2.4–207.6	7.1×10^{3}–1.6×10^{5} (65249.6)	7.1×10^{-6}–5.1×10^{-5}	3.2×10^{-2}–6.3×10^{-1} (2.2×10^{-1})
Scroll decanter centrifuge	1.4×10^{-4}–6.5×10^{-3}	0.8–1.5×10^{3}	1.5×10^{2}–8.4×10^{3} (3328.0)	1.4×10^{-4}–7.4×10^{-3}	7.5×10^{-4}–3.2×10^{-1} (6.6×10^{-2})

Values in brackets ( ) are average values.

3.3 Integration of Assessments

Fig. 7 shows the hierarchy structure of the decision-making for biomass separation equipment selection. The top level is the goal of the decision-making, which in this case is the selection of biomass separation equipment. The second level of hierarchy is the two criteria for selecting equipment, i.e., separation performance and energy consumption, which are equally important for the purpose of this example. The third level consists of various subcriteria for the separation performance criterion in the previous level. The lowest level contains the different alternatives for biomass separation equipment. It is necessary to note that AHP assumes no relation amongst criteria and subcriteria. If there is any relation between criteria and/or subcriteria, a generalized version of AHP, the analytic network process (ANP) [35], could be used instead.

Pairwise comparisons between subcriteria with respect to criteria in the higher level and between alternatives with respect to criteria and subcriteria in the higher level was performed to obtain the priorities of the criteria, subcriteria, and alternatives in the form of a judgement matrix. The example question asked to experts and/or decision-makers for pairwise comparison can be formulated as "In terms of separation performance, how many times is solid dryness more important than the capacity factor?" to compare amongst subcriteria or "With respect to solid dryness, how many times is a hydrocyclone preferable over a disc stack centrifuge?" to compare amongst alternatives.

Expert knowledge and preference from decision-makers are used to compare amongst criteria and subcriteria. In this case, the consensus vote from the authors as a synergistic group is used as all decision-makers suggested the same hierarchy for the decision problem. The authors reached an agreement on the value of each entry in a matrix of pairwise comparisons amongst subcriteria with respect to separation performance criterion, as indicated in Tab. 6.

In total, there are ten comparisons at the criteria and subcriteria levels. Information in Tabs. 4 and 5 as well as the consensus vote from the decision-makers are used to compare amongst alternatives with respect to a criterion or subcriterion. For example, a scroll decanter centrifuge is preferable than a hydrocyclone with respect to the solid product dryness subcriterion and a value of 1/4 is assigned for the hydrocyclone-scroll decanter comparison based on the information from Tab. 4. Expert knowledge from the authors is also useful when comparing alternatives whose specification for a certain criterion show a large difference. For example, a disc stack centrifuge is preferable than a hydrocyclone with respect to the capacity factor criterion as demonstrated in Tab. 5. The consensus vote from the decision-makers result in a value of 1/8 to be assigned

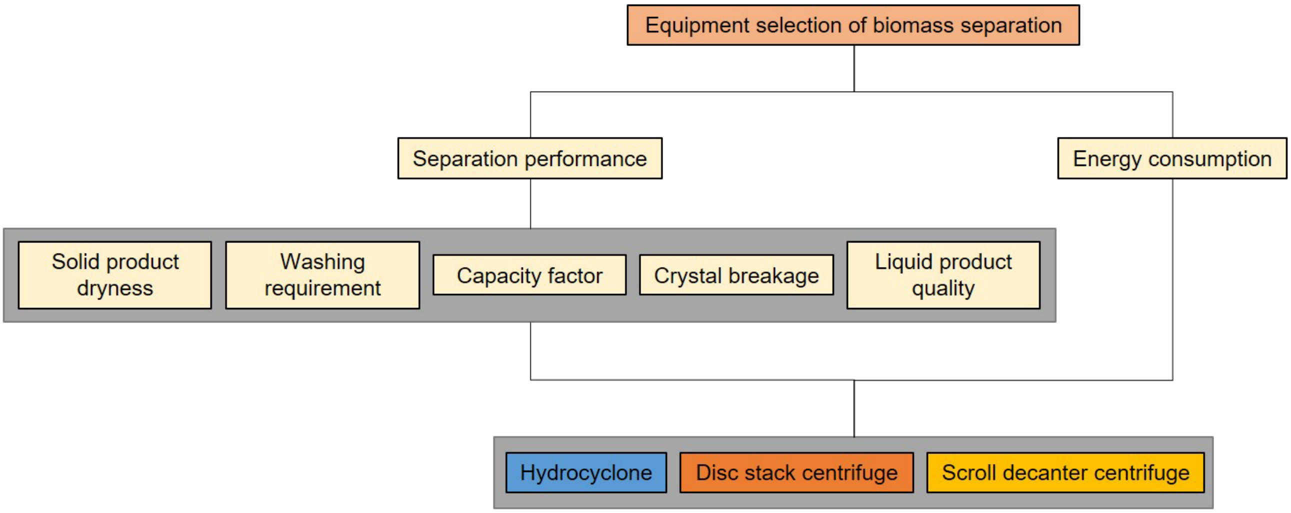

Figure 7. Hierarchy in AHP decision analysis for biomass separation equipment selection.

Table 6. Example of judgement matrix of pairwise comparison amongst subcriteria with respect to separation performance criterion.

	SC1	SC2	SC3	SC4	SC5	Relative weight
SC1	1	4	¼	3	1	0.20
SC2		1	¼	½	1/3	0.06
SC3			1	3	2	0.42
SC4				1	¼	0.09
SC5					1	0.23
						CR = 0.06

SC1: solid product dryness; SC2: washing requirement; SC3: capacity factor; SC4: crystal breakage; SC5: liquid product quality.

for this comparison. In total, there are 18 comparisons at the alternatives level with respect to criteria and subcriteria.

After the judgement matrix is established, the derivation of relative weights is performed using the eigenvalue method [33, 36]. The goal is to find a set of relative weights such that when slight inconsistencies are introduced through pairwise comparison, relative weights should vary only slightly. Based on the eigenvalue method, the consistency ratio is calculated for each comparison and found to be 0 for all comparison which is less than the threshold of the consistency ratio, i.e., 0.1, indicating the judgements at the alternatives and criteria/subcriteria levels are consistent as displayed in Tab. 7. This table also shows the relative weights of each alternatives with respect to each criterion and subcriterion, and the overall weights of each equipment as the basis for equipment ranking. In this example, the hydrocyclone was ranked at the top, followed by the disc stack centrifuge and the scroll decanter.

The last step of the decision process is the sensitivity analysis, during which the input data are modified to assess the impact on the results. In this example, the sensitivity analysis was performed by varying the weights of the criteria on the second level of hierarchy. This allows a set of criteria weights favored by the decision-makers to be fed into the decision model. This produced a different prioritized list of alternatives for the decision-makers to assess the change on the ranking of the equipment.

Figs. 8 a and 8 b illustrate the sensitivity of this ranking with respect to the change on the separation performance and energy consumption weights, respectively. Fig. 8a shows that if the weight for separation performance is greater than 0.67, the disc stack centrifuge becomes the preferred choice, whereas before that point the hydrocyclone remains the best alternative. Similarly, in Fig. 8 b it can be observed that if the weight for energy consumption is greater than 0.33, the hydrocyclone becomes the preferred choice, whereas below that value the disc stack centrifuge is the best alternative.

4 Conclusions

This paper demonstrates that MCDA is an appealing and systematic approach for synthesizing and organizing information to support the decision-making process for the selection of biomass separation equipment. The proposed methodology ensures that all the process requirements and criteria for selecting an optimal biomass separation equipment have been considered satisfactorily in the first stage. As observed, the methodology proposed in the first stage is easy to apply and can be used as a rapid decision-making tool for the equipment screening of a biomass separation process. In the second stage of the methodology, the selection of biomass separation equipment is carried out by means of the AHP method.

As demonstrated in the example, AHP is well-suited to be applied with different criteria. As it was demonstrated, the AHP method is based upon criteria that can be derived from knowledge of the equipment specification and experimental results. A list of criteria was suggested in Tabs. 4 and 5, but it is important to highlight that decision-makers could add new criteria to the list or just consider those criteria that better fit their specific problem and information. This framework can be employed to aid scientists and engineers on selecting the optimal equipment and can be extended to other products and processes.

Table 7. Relative weights of alternatives with respect to each criterion and subcriterion and the overall weight of alternatives, and consistency ratios from pairwise comparison.

Criterion/subcriterion	Alternatives			*CR*
	Hydrocyclone (conical reverse-flow)	Disc stack centrifuge	Scroll decanter centrifuge	
Energy consumption	0.77	0.06	0.17	0.00
Solid product dryness	0.14	0.29	0.57	0.00
Washing requirement	0.33	0.17	0.50	0.00
Capacity factor	0.00	0.95	0.05	0.00
Crystal breakage	0.44	0.37	0.19	0.00
Liquid product quality	0.44	0.11	0.45	0.00
Overall weight	0.48	0.29	0.23	
Rank	1	2	3	

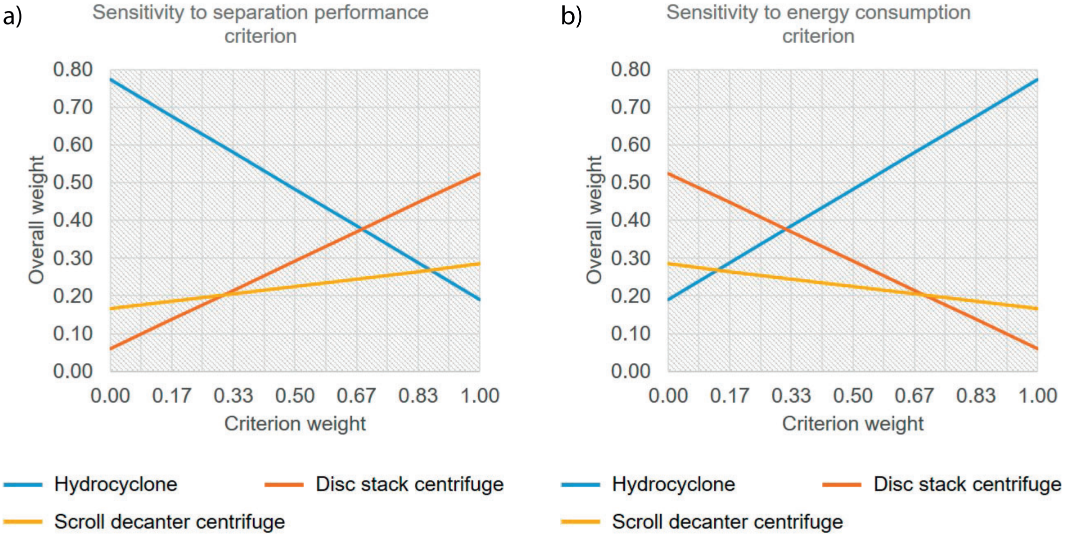

Figure 8. Sensitivity analysis on weight of criteria with respect to unit operation selection: (a) separation performance criterion; (b) energy performance criterion.

However, there is not a single right answer in MCDA. The notion of optimum in MCDA is rather a trade-off between criteria to select the equipment optimally. The use of different MCDA methods is possible, provided that the method meets the decision problem characteristics and the decision-maker can interpret the results correctly. The purpose is to provide insight to help the decision-makers to take better-informed decisions, to clearly understand the problem at hand, and to get structured information of priorities and values from the technology experts on the evaluated biomass separation processes and unit operations. Furthermore, MCDA can be applied to guide decision-makers in identifying a course of action when selecting equipment, while promoting transparency in the process.

The strength of MCDA also lies on its adaptability for sensitivity analysis. The sensitivity analysis is performed to answer decision-makers' 'what-if' type of questions. Here, different weights for the criteria were evaluated to assess their impact on the ranking of biomass separation equipment for the process studied. The results from a sensitivity analysis are useful for the decision-maker to determine how flexible the resulting equipment is to changes in the weights assigned to the criteria, given any existing constraints. The decision-maker can also use the sensitivity analysis results if there are any changes in circumstances in the future, allowing a more consistent and better-informed decision to be made.

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Symbols used

CI	[–]	consistency index
CR	[–]	consistency ratio
d	[µm]	particle 50 % cut-size diameter
g	$[\mathrm{m\,s^{-2}}]$	gravitational acceleration
i, j	[–]	criteria
n	[–]	order of judgement matrix
Q	$[\mathrm{m^3h^{-1}}]$	volume flow rate
RI	[–]	random consistency index
v	[–]	judgement value
v_g	$[\mathrm{cm\,s^{-1}}]$	gravity settling velocity
$\mathbf{X}$	[–]	example of biomass product

Greek letters

$\lambda_{\max}$	[–]	largest eigenvalue of judgement matrix
μ	[mPa s]	dynamic fluid viscosity
$\Delta\rho$	$[\mathrm{kg\,m^{-3}}]$	density difference between phases
Σ	$[\mathrm{m^2}]$	capacity factor

Abbreviations

AHP	analytic hierarchy process
ANP	analytic network process
MCDA	multicriteria decision analysis

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