Advancing the Circular Economy Through Organic by-Product Valorisation: A Multi-criteria Assessment of a Wheat-Based Biorefinery

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Abstract

The transition toward a circular and biobased economy requires the biorefineries and bio-based industries to become more resource efficient with regards to their waste and by-product management. Organic by-products and waste streams can be an important source of value if used in feasible pathways that not only have a low environmental impact but also preserve or recover their energy, nutrients, and other potentially valuable components. Through development of a multi-criteria assessment framework and its application on a real case, this article provides methodological and practical insights on decision making for enhanced by-product management. Our framework includes 8 key areas and 18 well-defined indicators for assessing the environmental performance, feasibility, and long-term risk of each alternative. We studied six different management options for the stillage by-product of a Swedish wheat-based biorefinery and our results shows that the most suitable options for this biorefinery are to use the stillage either as animal fodder or as feedstock for local biogas production for vehicle fuel. This multi-criteria approach can be used by bio-based industrial actors to systematically investigate options for by-product management and valorisation for a circular and bio-based economy.

Graphic Abstract

Keywords Bio-based · Waste management · By-product management · Industrial symbiosis · MCA · Feasibility assessment

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Statement of Novelty

This research contributes to the important area of by-product management in bio-based industries. It has a broad system view when assessing the by-product management alternatives and includes environmental and economic

performance, as some have studied before, but also a focus on feasibility and risk-related indicators. This is to better show the actual implications of different alternatives both for the industry and society. The research also highlights the importance of suitable waste and by-product management to become more resource efficient in the forthcoming bio-based and circular economy.

Introduction

A growing body of evidence shows that industrial and developing societies' historical dependency on fossil fuels and other non-renewable resources is a major driving force behind climate change and several growing environmental and social challenges across the world. Therefore, societies and industries should reduce their dependency on non-renewable resources, increase their resource efficiency, and try to establish more sustainable patterns of production and consumption. An important part of this is better utilisation of bio-based resources to produce renewable and sustainable materials, energy carriers, and services in a so-called circular and bio-based economy [1]. In particular, the by-products and wastes from bio-based industries—defined as industries that mainly use renewable biological resources to produce bio-based products and biofuels—can improve the profitability and sustainability of industries if handled well [2, 3]. However, for any given bio-based industrial system, not all by-product and waste management alternatives are equally suitable or interesting. Some of the alternatives may be easier, cheaper, and faster to implement and have better technical and economic feasibility compared with others. Similarly, some of the alternatives may lead to better environmental performance in relation to others. Therefore, proper assessment of the suitability of different management options can help the decision-makers to select more appropriate options.

To improve sustainability in industries, a broad systems perspective, including the improved use of by-products and waste management, is needed. This might not be possible within the same facility, as specialised technologies could be needed to valorise by-products and manage the waste streams [4]. While industries tend to focus on their core business, products, and supply and demand, they can improve their by-product and waste management through special interorganisational collaborations, typically referred to as industrial symbiosis [5–7]. Especially, bio-based industries might benefit from nearby collaboration as by-products, and organic wastes can be bulky and of low volumetric value, and therefore not economical to be transported over long distances [8–11]. Improving resource efficiency and circularity through better utilisation of by-products or using wastes

as raw materials for other processes can contribute to more sustainable industries and a more circular economy [12].

Existing studies in the literature tend to focus on either performance or feasibility, which corresponds to a gap between assessing the expected sustainability effects and assessing the feasibility for implementation [3, 13]. Many studies are focused on assessing the potential impacts of the solutions on the society or environment and pay little attention to feasibility assessment and the conditions that are required for their implementation (see, [14]). On the other hand, those that consider feasibility assessment tend to have a narrow focus on technical or economic issues and do not assess the energy and environmental performance of the alternatives from a life-cycle perspective (see, [15–17]). In short, assessing by-product and waste management alternatives in bio-based industries can benefit from relatively simple methods that allow the systematic assessment of “feasibility” and “environmental performance” under a single, coherent framework.

Indicator-based methods are closely linked to multi-criteria approaches and multi-criteria analysis (MCA). These methods are flexible by nature, open to participatory processes, can be used to assess aspects that require both quantitative and qualitative information, and, depending on the ambition of the participants, can be used as a framework for incorporating a broad set of issues into the decision-making process [18, 19]. In our view, one of the most important reasons for selecting a multi-criteria approach is to have a multi-dimensional view on a decision which requires a plurality of aspects and methods to be used under a common procedural framework (cf. [20]). For example, a multi-criteria approach can be used if it is expected to quantitatively compare the environmental performance of several alternatives by using life-cycle assessment (LCA) and at the same time it is required to compare the feasibility of alternatives from technical, organisational, or institutional perspectives through qualitative analyses. Common approaches to MCA consist of defining a problem, identifying alternatives that have to be analysed and compared (referred to as scenarios), selecting and defining a set of criteria and indicators, weighting and recommendations [21]. With MCA, it is possible to widen the scope as much as deemed relevant, important, and appropriate by the researchers and the participants involved. This is due to the loose analytical link between different criteria and indicators and the possibility of having qualitative indicators that can be used to represent aspects that are difficult to numerically define, for example, contextual issues that can influence the feasibility.

Hagman et al. [22] studied several alternatives for a wheat-based biorefinery in Sweden regarding its stillage (by-product) management. To identify the most sustainable option, they performed a life-cycle assessment on the greenhouse gas (GHG) emissions for each of the identified

alternatives. They also included additional sustainability aspects, namely, energy balance, nutrient recirculation, and economic analysis. Although this analytical and quantitative study included a relatively broad view on sustainability assessment of by-product management alternatives, it lacked feasibility-related issues that are important for the implementation. This issue requires a more flexible assessment method that can combine both quantitative and qualitative indicators, something which was difficult to do through the life-cycle assessment (LCA). In this paper, we return to the same case and perform a broader assessment of by-product management alternatives through multi-criteria analysis (MCA).

Our aim is to assess the alternative options for by-product management in the studied case and to highlight each option's pros and cons from multiple perspectives that not only includes aspects such as environmental performance but also other issues such as feasibility and risk. For this purpose, we develop a multi-criteria assessment framework which is tailored for assessing by-product management alternatives and development options for biobased industries. The key methodological contribution of our paper is its broadened and multiple perspectives that expands the environmental and economic assessment and includes feasibility and long-term risk as well. If the sustainability assessment of by-product management is supposed to be useful as decision support for bio-based industries, it requires an integrated assessment regarding technological, economic, environmental, regulatory, organisational, and sector-specific considerations. In this paper we demonstrate how such an approach can be applied on a real case. We will also discuss the methodological issues regarding assessments of by-product management in bio-based industries using analytical

approaches such as LCA and procedural approaches such as MCA.

Method

Our approach toward multi-criteria analysis was based on the methods and recommendations by Feiz [23], Feiz and Ammenberg [21], and Lindfors et al. [3] and consisted of five main steps (Fig. 1).

The first step was to define the goal of the study, which, as it was mentioned, was to assess the environmental performance, feasibility, and risk of by-product management alternatives (scenarios) in the studied biorefinery from the industry gate to final usage. This biorefinery is situated in the south of Sweden in an agricultural area. It started as a starch production facility, but its product-portfolio has expanded over the years. The biorefinery is positioned next door to the municipal waste incineration plant, and since 2011, there has been a biogas plant located 3 km from the facility. A large amount of stillage is produced considering the input (Fig. 2). The stillage has a Total Solids (TS) content of approximately 7% and a relatively low nutrient content.

The second step was to identify the alternatives for by-product (stillage) management (Fig. 3). Similar alternatives were investigated by Hagman et al. [22], and more details can be found there.

Many of these alternatives have been discussed in literature since many decades ago [24], but they are also discussed in later literature [25]. The most common practise is to use the stillage directly as a wet fodder transported to customers by truck which in this paper we consider as the reference case. In some cases, the stillage is distributed as

Fig. 1 Overview of the multi-criteria method and the main steps; Define the goal, Identify alternatives, Define multi-criteria assessment framework, Assess the alternatives, Interpret the results

Fig. 2 Overview of the main biomass input, main products, and by-products of the studied wheat-based biorefinery in Sweden. Inputs such as water and energy or outputs such as wastewater and emissions are not shown. The focus of this study is on the sustainability assessment of management alternatives (scenarios) for the by-product (stillage)

Fig. 3 Overview of the alternative by-product management options (scenarios) for the studied wheat-based biorefinery

fertiliser when no other solutions were found. An incineration scenario is included as the biorefinery is situated next door to an incineration plant which sometimes need to moisturise their received wastes. There are also three scenarios related to biogas production; produce gaseous biofuel for transportation by anaerobic digestion in a distant biogas plant; produce gaseous biofuel for transportation by anaerobic digestion in a local biogas plant; and produce heat and electricity by anaerobic digestion in a local biogas plant. In all biogas scenarios it is assumed that the digestate is used as biofertiliser. Also, the methane potential is based on the stillage properties, but it is assumed that in practice the stillage will be co-digested with other feedstocks. In Sweden it is common with biomethane as a fuel and the market is expected to grow in future [26], while biogas for heat and power is not as common due

to the low prices of heat and power. To ensure that these alternatives were still relevant, they were discussed again with the involved stakeholders, especially the representatives from the biorefinery itself.

The third step was to define the multi-criteria assessment framework, tailored for development alternatives in bio-based industries. The framework's overall structure and its conceptual basis were largely based on earlier work by Feiz and Ammenberg [21] and Lindfors et al. [3], but the new framework itself had several differences to make it suitable for assessing by-products from biorefineries. The framework consisted of a few overall criteria directly derived from the goal of the study and discussions with the stakeholders: the criterion of *environmental performance*, the criterion of *feasibility* (for implementation), and the criterion of *low risk* (in the long run). These criteria were the guidelines that allowed

the identification of relevant and important issues to the framework.

Each of these criteria was broken down into a few key areas and corresponding key questions, and in turn, each of these key areas was represented by one or more indicators (Fig. 4). It was possible to assign a key area—and its corresponding key question—to more than one criterion. The indicators were defined to create a measurable, consistent, and comparable way of answering the key questions. The definitions of the indicators were provided by qualitative and sometimes quantitative scales.

The scale used in the analysis has five levels: Very Poor, Poor, Fair, Good, and Very Good. We have provided the definitions of the scales for Poor and Good, while the other levels can be interpreted as worse or better than those definitions, or if the situation is somewhere in-between, resulting in Fair. These adjectives are commonly used in the literature; see, for example, Taylor-Powell [27].

An overview of the multi-criteria assessment framework, the key areas and key questions, and the indicators are presented in Table 1. The detailed definitions of the indicators and their scales are presented in Online Resource 1.

One quantitative and one qualitative indicator are presented below to illustrate how descriptions and scoring descriptions look in the assessment.

One of our quantitative indicators chosen, Climate change performance, estimates the GHG emissions from by-product management, considering system expansion. This means that transportation (stillage, biofertiliser, and biogas), production (biogas, biofertiliser, heat, electricity), emissions from fertilised fields as well as avoided emissions (products from stillage substituting fodder, fertiliser, diesel, heat, or electricity) are included. The indicator shows how the GHG-emissions, corrected by the value of the produced products in the scenario, differ compared to the reference case which is set to the Fodder scenario in this study (Table 2).

The second example is a qualitative feasibility indicator, Institutional support and efficient administration. The scale definition includes several different measures, which can all be required, or at least some required, and need to be fulfilled for the different results. The indicator shows if the existing regulatory conditions support or hinder the studied scenario's implementation and whether the required administrative processes are easy and efficient or are difficult and inefficient (Table 3). When assessing qualitative indicators informants have been important to give their view on qualitative aspects,

while literature and documentation regarding the area have been used to support the results.

We also included a certainty assessment for each of the assessed indicators by assigning 1 to 3 stars (*, **, ***) based on how certain we have been on the assessment. If there was not enough information, or there were major discrepancies, contradictions, and doubts regarding some of the information (from the respondents or the studied literature), an indicator might only receive one star (low certainty). On the other hand three stars (high certainty) were given if sufficient credible and consistent information were available based from the interviews and literature.

The fourth step was the actual assessment. Based on earlier interviews with some of the actors and available information from the literature and websites, a preliminary assessment was performed to try out the framework. In several cases, a range of the assessed indicators was presented. In cases where the authors were uncertain or lacking information, the indicator was left blank. In some cases, adjustments to the definitions of the scales were performed. Three workshops were held with involved actors using the developed multi-criteria framework as a basis to improve the assessment. All workshops were conducted face to face, and the participants could ask questions at any time something became unclear. Representatives from the existing biogas plant, incineration plant, and biorefinery participated in individual workshops. In the first workshop, a project leader and a production manager from the biogas plant who had been involved since it started six years earlier participated and provided input on the use of stillage as a feedstock for the biogas plant. The second workshop was with a senior project leader from the incineration plant who knew about the technical operation of the plant and the use of different fuels including stillage. The third workshop was with representatives from the biorefinery. An R&D engineer and a stillage expert responsible for its distribution to different customers participated (both had been in their positions for a few years). The R&D engineer could answer questions regarding strategies of the biorefinery and the environmental impact of the scenarios, while the stillage expert provided detailed information about the stillage characteristics and how the company have used the stillage over the years. They were sent a document containing the description of the framework in advance, where all indicators and scales were presented. There were instructions on how to read the descriptions of the indicators. The preliminary results collected by the authors were included to illustrate how the assessment can be made. All indicators were discussed during the workshop, and the participants with expert knowledge regarding the activities of their organisation could comment and add information. In most cases, the gathered information was sufficient for the participants to assess the indicators (i.e., give it a result on the predefined scale; see Table 5). The data gathering was completed through literature studies and calculations for quantitative indicators throughout

Fig. 4 The structure of the developed multi-criteria assessment framework consisting of criteria, key areas and key questions, and indicators

Table 1 Overview of the multi-criteria assessment framework for comparing different by-product management options. The framework consists of 3 criteria, 8 Key areas and key questions, and 18 indicators

Key area	Key question	Indicator
Energy and environmental performance (environmental performance)	Will this development scenario contribute to a more efficient energy use, more efficient nutrient recycling, and better environmental conditions?	Nutrient recirculation Primary energy performance (Compared to reference) Climate change performance (Compared to reference) Local/regional environmental impact
Economic feasibility (feasibility)	Is this development scenario profitable or cost-efficient?	Profitability or cost efficiency ^a (compared to reference) Transportation efficiency (compared to ref. case) Reduced load on waste management systems (compared to reference)
Geographical and physical suitability (feasibility)	Is the location and its surrounding environment physically and geographically suitable?	Geographical and physical suitability
Technical feasibility (feasibility)	Are the required technologies and infrastructures—considering the full life-cycle—available and ready to use?	Technological readiness Infrastructural readiness
Organisational feasibility (feasibility)	Are all the required actors with suitable knowledge (including technical/organisational knowledge and considering the full life-cycle), available and cooperating toward the common goal of implementation of this development scenario?	Actor's readiness
Public acceptance and institutional feasibility (feasibility)	Is this development scenario supported by the governmental rules and regulations, public institutions, local communities, and the general public?	Public acceptance Institutional support and administration Planning horizon and clarity of business
Market accessibility and control (feasibility)	Is it possible to control/secure the provision of the required energy and materials and the market for the products and by-products?	Upstream accessibility and control Downstream accessibility and control Sidestream accessibility and control ^b
Risk avoidance (low risk)	Considering the full spectrum of business and social activities, does this development scenario appear to be viable and low-risk in the long run, that is, resilient?	Long-term risk-avoidance Biocascading ^c

^aCost-efficiency is here defined as profitability of the biorefinery actors in comparison with reference case

^bSidestreams are defined as material or energy flows between different actors within the studied system before final products are produced

^cBiocascading is the utilisation of biomass based on the assumption that it is better to first produce high value products and then low value ones. This can be a strategy for improving the long-term resilience of the production system

Table 2 Scales for the indicator “Climate change performance”

Value	Scale definition
	Considering the reference case, and the valorisation factor (K_v) defined as $\frac{\text{Value of products}_{\text{Scenario}}}{\text{Value of products}_{\text{Reference}}}$, and estimated using the following formula: Climate change performance = $\frac{\text{GHG}_{\text{Scenario}} \times K_v - \text{GHG}_{\text{Reference}}}{\text{GHG}_{\text{Reference}}}$
Good	This development scenario has 10–30% lower GHG emissions compared to the reference case (after correction for the value of the products)
Poor	This development scenario has 10–30% higher GHG emissions compared to the reference case (after correction for the value of the products)

the whole process (Online Resource 2). As a result of these inputs and interactions, additional adjustments to the assessment framework were made.

The fifth and last step of the method was the interpretation of results. The multi-criteria interpretation is based on the assessment results (Step 4) and qualitative discussion

Table 3 Scales for the indicator “institutional support and efficient administration”

Value	Scale definition
Good	Regarding this scenario, all of the following points are correct: There is some support—such as mandatory targets, tax exemptions, or subsidies—in the existing or forthcoming regulations or guidelines The administrative processes—for example, those related to obtaining the required permits—are reasonable, easy, or efficient
Poor	Regarding this scenario, any of the following points are correct: There are some regulatory barriers—such as bans or taxes—in the existing or forthcoming regulations or guidelines The administrative processes—for example, those related to obtaining the required permits—are burdensome or inefficient

about the pros and cons of each alternative. The three criteria (environmental performance, feasibility, and low risk) are interpreted using a binary scale of either being “suitable” or “complicated or problematic” (Table 4) to provide an overview.

We have also discussed the methodological and practical differences between the multi-criteria-based approach of this paper and the life-cycle-based approach of Hagman et al. [22].

Results

The results of the multi-criteria assessment of the considered scenarios, as defined in the method (and in Online Resource 1), together with the stakeholders participating in the workshops, were achieved regarding the different by-product management alternatives (Table 5). Motivations and estimations for the results can be found in Online Resource 2.

The results indicate that the reference case, which is ‘Fodder’, generally performs well and is a suitable way of managing the stillage. In addition to that, ‘Local Biogas for Vehicle Fuel’ is a suitable alternative concerning most of the assessed indicators (and key areas). The main feasibility drawback of ‘Distant Biogas for Fuel’ or ‘Local Biogas for heat and power’ is the low economic incentives for the stillage owner. ‘The Distant Biogas for Fuel’ scenario has low scores in several indicators due to the increased transportation. The ‘Fodder’ alternative stands out well compared to the other scenarios. Regarding the *reduced load on waste management systems*, the reference case (‘Fodder’) and all alternatives, except the ‘Incineration’, lead to no pressure on the waste management, which could be seen as Very Good.

However, since the scoring of this indicator is based on the reference case, the results are set to Fair as the situation in several scenarios is the same as the reference case. Using the stillage in ‘Fertiliser’ is possible but is not commonly used as it can only be applied to soils before crops are planted [25]. Distributing the stillage as fertiliser also increases the net cost for the biorefinery and Climate change performance and Primary energy performance are low also due to the low value of the stillage as fertiliser. The ‘Incineration’ option can seem practical from a transportation point of view since it can be pumped between the facilities, but due to the low dry matter content of the stillage, it is not feasible in such large quantities, although smaller amounts could be used to moisturise other wastes. ‘Incineration’, therefore, scores low in several aspects regarding performance, feasibility and risk. More detailed motivations for each score are found in Online Resource 2.

The certainty of the assessment is presented by *, **, or *** stars (Table 5). Some indicators are more difficult to evaluate, such as *long-term risk avoidance*, *institutional support and administration* and *local environmental benefits*. In those, there are uncertainties regarding time perspectives and actions from external actors. There are then some specific alternatives where two certainty stars are given to some indicators. For example, *downstream accessibility* of the biogas scenarios producing fuel has uncertainties in the gas market. Public acceptance is hard to evaluate for some of the scenarios, as all opinions might not be gathered. The distant biogas plant has lower certainty regarding *actors’ readiness* because it has been hard to estimate how many new contacts would be required and if we can assume customers for the products from the biogas plant are available or not. The incineration scenario

Table 4 A binary scale for the multi-criteria interpretation step (environmental performance, feasibility, and low risk)

Interpretation	Criterion of “environmental performance”	Criterion of “feasibility”	Criterion of “low risk”
Suitable		All indicators are assessed as Fair, Good, or Very Good	
Complicated or problematic		At least one indicator is assessed as Poor or Very Poor	

Table 5 Overview of the multi-criteria assessment results of six different alternatives for by-product management in the studied biorefinery case. The alternatives are Fodder, Fertiliser, Incineration, Distant Biogas for Fuel, Local Biogas for Fuel and Local Biogas for heat and power

Key area	Indicator	Fodder	Fertiliser	Incineration	Distant biogas for fuel	Local biogas for fuel	Local biogas for heat and power
Energy and environmental performance, nutrients and resource economy (environmental performance)	Nutrient recirculation	Very Good ***	Very Good ***	Very Poor ***	Very Good ***	Very Good ***	Very Good ***
	Primary energy performance ^a	(Reference)	Very Poor ***	Very Poor ***	Very Good ***	Very Good ***	Very Good ***
	Climate change performance ^a	(Reference)	Very Poor ***	Very Poor ***	Very Good ***	Very Good ***	Very Good ***
	Local/regional environmental impact	Good **	Fair (Poor) **	Fair **	Good **	Good **	Good **
Economic feasibility (feasibility)	Profitability or cost efficiency ^a	(Reference)	Very Poor ***	Very Poor ***	Very Poor ***	Fair ***	Very Poor ***
	Transportation efficiency ^a	(Reference)	Very Good ***	Very Good ***	Very Poor ***	Very Good ***	Very Good ***
	Reduced load on waste systems ^a	(Reference)	Fair ***	Very Poor ***	Fair ***	Fair ***	Fair ***
Geographical and physical suitability (feasibility)	Geographical and physical suitability	Good ***	Good ***	Poor ***	Poor ***	Good ***	Good ***
Technical feasibility (feasibility)	Technological readiness	Good ***	Good ***	Very Poor ***	Good ***	Good ***	Very Good ***
	Infrastructural readiness	Very Good ***	Very Good ***	Poor (Fair) **	Good ***	Good ***	Very Good ***
Organisational feasibility (feasibility)	Actor's readiness	Very Good ***	Good ***	Good ***	Good (Fair) **	Very Good ***	Very Good ***
Public acceptance and institutional feasibility (feasibility)	Public acceptance	Good ***	Fair **	Very Good (Good) ***	Fair **	Fair **	Fair **
	Institutional support and administration	Fair **	Fair **	Fair (Poor) **	Good **	Good **	Good **
	Planning horizon and clarity of business	Fair **	Fair **	Fair (Good) **	Very Good ***	Very Good ***	Very Good ***
Market accessibility and control (feasibility)	Upstream accessibility and control	Very Good ***	Very Good ***	Very Good (Good) ***	Very Good ***	Very Good ***	Very Good ***
	Downstream accessibility and control	Good ***	Fair ***	Very Good ***	Good **	Good **	Very Good ***
	Sidestream accessibility and control	N/A	N/A	Good ***	Good ***	Good ***	Good ***
Risk avoidance (low risk)	Long-term risk-avoidance	Fair *	Fair *	Poor **	Fair *	Good **	Good **
	Biocascading	Very Good ***	Fair ***	Poor ***	Very Good ***	Very Good ***	Good ***

^aThese indicators have scales based on the reference case

N/A Not applicable

is uncertain regarding *infrastructural readiness*, mainly because it is hard to know additional requirements and investment costs and how easily it can be organised, more information regarding these certainty scores is presented in Online Resource 2.

Interpretation of the Results

The interpretation of the multi-criteria assessment of the scenarios is performed qualitatively and using the scales explained earlier in order to assess their suitability (Table 5). A visual overview of the interpretation is presented regarding the three considered criteria (Fig. 5).

Two of the studied management alternatives, ‘Local Biogas for Fuel’ and ‘Fodder’, had no Poor or Very Poor results for any of the indicators, resulting in sustainable alternatives for stillage management concerning all the assessed criteria. A potential disadvantage for ‘Fodder’ is the risk of satisfying the nearby market. If our assessment were more dynamic and included potential expansions, then the *downstream accessibility* regarding ‘Fodder’ would most likely become Poor. In that case, the ‘Local Biogas’ scenarios would have had the advantage of managing larger amounts of stillage than a fodder customer.

Suitable scenarios regarding low risk and environmental performance are the two other biogas scenarios, ‘Distant Biogas for Fuel’ and ‘Local Biogas for heat and power’. The advantages regarding the environmental performance are the same as for the ‘Local Biogas for Fuel’ but are considered problematic (Very Poor profitability or cost-efficiency) due to the increased transportation in the ‘Distant Biogas for Fuel’ scenario, and the relatively low price on the stillage if biogas is turned into heat and power in ‘Local Biogas for heat and power’.

Scenarios that appear to be problematic from the environmental performance and feasibility perspectives are Incineration and Fertiliser, mainly due to the large water content of the stillage, decreasing the feasibility of the application, and therefore having Very Poor economic, primary energy and climate change performance. Incineration is also considered Poor in long-term risk as there are discussions regarding banning organic wastes for incineration or the overall reduction of the wastes being incinerated. The results are consistent with other studies of similar cases, including Hagman et al. [22] and Bernesson and Strid [25]. However the multi-criteria assessment framework in this paper was developed to create more complete decision support as it

includes feasibility-related indicators and indicators such as nutrients flows that tend to be important for many bio-based industries [3].

Discussion

Why Multi-criteria Approach?

Assessing different by-product management alternatives for a biorefinery (or a bio-based industrial process) can be viewed as a multi-dimensional issue. Different questions should be raised, each addressing a certain aspect of the assessment which in turn must be answered in a comparable manner so that it become possible to compare different alternatives with each other (from that particular aspect). For example, one can ask, “which alternative is more cost-efficient?”, or “which alternative is sounder in terms of environmental impact; be it climate impact mitigation, better energy use, or other types of impacts?”, or “is this alternative allowed under current regulatory system?” Depending on the question, different assessment methods may be needed which can be of an analytical nature [23, 28]. If the question is about GHG emissions, life-cycle assessment (LCA) can be a suitable assessment method. Or, if the question is about nutrients recovery through the system, a detailed mass-balancing of the nutrient-bearing flows can be suitable. Furthermore, if the question is about regulatory aspects, a qualitative study of the governing regulations regarding waste management and reporting schemes can be suitable. In short, if the problem must be addressed from different dimensions and by different methods and still had to be able to provide a systematic a comparable output, a procedural and multi-dimensional method of analysis is required [23]. Through better structuring of problem-related knowledge, systematic identification strengths and weaknesses, and integration of stakeholders into the decision-making process, multi-criteria can help overcoming the implementation barriers [18].

It is our position that regardless of what we call this multi-dimensional method, they can be generally referred to as multi-criteria approaches. The main methodological contribution of our paper is the provided multi-criteria assessment framework for systematic comparison of by-product management alternatives for a biorefinery (or a bio-based industrial system). Also, we have applied this method on a real case to demonstrate how it can be used in practice. Nevertheless, it is important to note that the suggested multi-criteria assessment framework is malleable depending on the purpose of the assessment and the priorities of the involved stakeholders.

Another methodological contribution of our paper is our elaboration on the development of a few well-defined

Fig. 5 Overview of the multi-criteria assessment results: interpretation of the three considered criteria (environmental performance, feasibility, and low risk)

indicators for by-product management within a biorefinery or a bio-based industrial system, with scales consisting of clear quantitative or qualitative thresholds or demarcations. This is in contrast with the “hard” MCAs that tend to have less well-defined indicators (e.g. numerical scales without providing a detailed definition of each step) and focus on quantitative aggregation and comparison of results through weighing and scoring to arrive at a “decision” (see [29–31]). Our approach avoids this analytical and quantitative aggregation and prioritise assimilation and summarisation of knowledge, stakeholder involvement, and providing refined input into decision making process. Such “soft” MCA approaches have been previously used for other types of questions in a biobased and circular economy [3, 21, 23, 32].

In the previous study of the same biorefinery by Hagman et al. [22], quantifications were performed regarding the GHG emissions, energy balance, net income/cost for the biorefinery, and nutrient recirculation regarding the different by-product management options. Even though that study aimed to include a broad assessment and a life-cycle perspective, their method still focused on quantifiable environmental or economic performance and left out important areas related to feasibility and risk assessment. These aspects are highly relevant for decision-makers when faced with different choices regarding by-product management alternatives and were therefore included in our MCA. In our developed multi-criteria assessment framework, we have shown how results from analytical methods such as LCA can be incorporated side by side qualitative assessment.

LCA and MCA can be utilised as complementary methods for sustainability assessments of different by-product and waste management options in bio-based industries [23, 33]. An MCA can be used for screening several alternatives with a wide scope and from many different aspects, while an LCA (or LCC) can be used for in-depth assessment of certain quantifiable aspects. Combining MCA and LCA can be useful in situations where both wide and deep assessments are required. MCA can be useful for early assessment to map the available knowledge in all important areas and clarify additional in-depth analyses that may be required. LCA or other analytical methods, such as mass-balance, energy analysis, or economic analysis, can then be commissioned to fill in the gaps and provide the required information. For example, in this study, the overall MCA framework was used to assess different by-product management alternatives in a biorefinery, but it included indicators that could be assessed via quantitative methods such as LCA (e.g. climate impact or primary energy performance). The MCA method can be used by practitioners both within industry or in municipal roles where business development is assessed. Dynamic aspects could be included where changes over time are considered, such as in regulatory changes and expansions, to improve the method even more. An assessment like this

example could also benefit from *mixed scenarios*, where, for example, parts of the stillage are used as fodder and parts for biogas, to assure several markets can get satisfied.

Choice of Indicators

The feasibility indicators included in our study (including policy support, technical feasibility, business implications, public acceptance, and regulatory feasibility) are suggested in earlier research [34, 35]. Through these indicators, decision-makers can receive insight regarding what alternatives are more practical to realise. This framework also included the criterion of low-risk through which the decision-makers can become aware of medium- to long-term risks related to the biorefinery’s by-product management and external circumstances. Risk- (and feasibility-) related indicators such as hazards, practical barriers, resource availability, and market situation have been suggested by Elghali et al. [34] and Keller et al. [35]. Stakeholders highlighted these types of indicators in interviews, as they connect to real-world issues that can stop too complex or fragile projects in the long term. When making decisions for by-product management alternatives, it is important to consider feasible solutions with low long-term risk, for example, in view of their perceived sustainability in the long run. For example, in the assessment of ‘Fodder’, we have assumed that the demand in animal husbandry will not decrease in the future. But if meat or dairy consumption decreases in the future, the need for fodder will decrease too, although, even in such a situation, it is the imported soy fodder that is likely to be reduced first.

Not all indicators related to environmental performance are always considered relevant by the involved stakeholders in the different studies. For example, ozone depletion, acidification, and eutrophication are sometimes not considered to be as relevant indicators as climate change, biodiversity, working conditions, water use, ecosystem functions, and the use of various resources when assessing bio-based value chains [36]. However, in our framework, we dedicated an indicator to nutrient recirculation to highlight its importance. Nutrients are inherently linked to biomass production and bio-based processes and can play a notable role in better nutrient recirculation in a biobased and circular economy [37]. The importance of nutrient recirculation becomes clearer in light of the increased global demand for the limited supply of phosphorous fertilisers (P) and energy-intensive nitrogen fertilisers [38, 39]. Studies that discuss nutrient recirculation do not always explicitly assess the amount, quality, and significance of the recirculated nutrients and instead may be focussing on the practical aspects of recirculation (cf GarciaAlba et al. [40]). Both Hagman et al. [22] and our assessment in this paper include estimates of the potential nutrient recirculation, but the way of presenting

the results differs. In this MCA, the percentage of nutrients in the by-products that are potentially recirculated is estimated, while in Hagman et al. [22], the amount of nutrients recirculated is presented in relation to the amount of fertilisers needed to grow the wheat used within the biorefinery. Coherence and transparency regarding such estimates could facilitate for decision-makers when comparing different studies. Another difference on this point was that the MCA also saw fodder as a nutrient recirculation option, while Hagman et al. [22] only looked into nutrient recirculation as a substitute for mineral fertilisers and did not consider nutrients recirculation via other solutions of by-products.

Stakeholder Participation

Since the MCA integrates different types of knowledge—including the subjective and partial perspectives of the involved stakeholders—the results of the assessments (at least for some of the indicators) is to some extent case-specific and depends on the stakeholder participation [18]. However, this is not necessarily a drawback (as long as the MCA is performed in a transparent and disciplined manner), since one of the main aims of the MCA is to support decision-making toward implementation of a suitable alternative. Therefore, only a solution that is deemed reasonable and suitable by the involved stakeholders (here the representatives from the biorefinery, incineration plant, biogas plant, and so on) have a chance to be implemented. Consequently, the stakeholder participation is a very important as stakeholders are directly or indirectly involved in the activities concerning the development, operation and impact of a biorefinery. Stakeholders can be related to feedstock production and supply, energy and utility systems, waste management, technical processes, technology provision, financing, policy-making, planning, nearby living environment, and end use [34]. Stakeholders may be affected in positive or negative ways, and therefore, a participatory approach—despite its additional complexities—can significantly improve the reliability and applicability of the results. Compared to Hagman et al. [22], the importance of participatory processes was more visible in this study. In Hagman et al. [22], data was collected from interviews with the stakeholders, but the authors themselves estimated the results (by LCA modelling). However, in this study, the only way to reliably assess some of the indicators was to hold workshops with the stakeholders and to get their insight and input. The workshops not only contributed to this assessment; they also had some positive impacts on the involved companies and organisations, as the participants came up with new ideas for a more circular economy. Performing a multi-criteria analysis and discussing a broad range of important aspects and indicators in a participatory manner can lead to learnings

that can influence future cooperation and development, inter-organisational synergies, and furthering the industrial symbiosis [41].

Biorefineries Role in the Circular Economy

Biorefineries' environmental and economic performance depends on the feedstock, logistics, process configuration, integration with nearby industries, and management of by-products [12, 42]. Extracting high-value products from bio-based materials may be hard to implement on a large-scale in a way that is also economically and environmentally efficient [12]. For example a wheat-based biorefinery, such as the one studied, may also look into the upcycling of straw to improve competitiveness even further [43]. This article has investigated the technologically mature solutions (for example, biogas production through anaerobic digestion), while emerging or untested technological solutions are not included, even if they have shown to be potentially value-adding in experimental scales (for example those reviewed by [44]). Nevertheless, biogas solutions are arguably always relevant to the drive toward a circular economy even when the bio-based materials are highly utilised and valorised. This partly because there will always be some low-grade wastes or by-products leftovers that can be effectively managed through anaerobic digestion [42] and energy balance of biorefineries may improve as well [45]. But, more importantly and in a broader sense, a circular economy cannot be achieved by merely non-biobased processes: closing the loops through biological processes and regeneration through technologies such as anaerobic digestion is an essential part of a circular and biobased economy [46]. Our method can help biorefineries and bio-based industries improve themselves by implementing more resource-efficient solutions related to organic waste and by-product management or product developments.

Conclusion

Bio-based industries need to improve their waste and by-product management to become more circular and resource efficient. In the studied case we developed a multi-criteria framework for assessing and comparing different by-product management alternatives of a biorefinery or biobased industrial system. We applied this framework on a wheat-based biorefinery and compared different ways in which it could manage its stillage by-product. The results of our assessment pointed toward producing biogas fuel in a local biogas plant, or to produce fodder as suitable candidates for by-product management.

In any bio-based industrial system, there can be several alternatives for by-product management to choose from, and each demands a considerable amount of time and resources to be implemented. Therefore, a broad and systematic assessment, like the multi-criteria assessment framework suggested in this paper, can help decision-makers to identify and learn about the most suitable management options. The novelty of our approach is our focus on by-product management in biobased processes (e.g. the nutrients recirculation aspect), combining performance-related issues with feasibility-related issues and long-term risk avoidance. Our method is developed to be relatively generic, so it can be used as a tool for assessing different development alternatives of any biobased industrial system concerning waste or by-product management.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s12649-021-01440-y>.

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Data Availability Some of the more detailed data is collected directly from active companies and are therefore not shared in its raw form. The data presented within the article and its online resources are the most important basis for the assessment results.

Declarations

Conflict of interest I suppose the research could be considered bias as the research is performed within BRC, but our interest lies in finding the most resource and energy efficient solutions and thus all the scenarios has been developed based on actions used in a real case and the assessment has been performed in the same way for each scenario.

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