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Sustainability and circularity assessment of biomass-based energy supply chain

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ABSTRACT

Climate change and other environmental consequences of socio-economic activities require a more sustainable and circular growth. At the same time, the limitation of the earth resource demands industries to improve resource efficiency and increase the rate of recycling of materials. There are several sustainable and circular alternatives that the industries may adopt. However, the question is that among these alternatives, which one should be selected for implementation for the highest sustainable and circular benefits. This study introduces a novel tool for assessing the sustainability and circularity of biomass-based energy supply chains, integrating multi-criteria decision-making methods with life cycle thinking approach. It evaluates five alternatives using a sustainability and circularity indicators, offering new insights into the deloyment of circular business models at companies in biomass-based energy supply chain. The tool is also applied to a specific rice straw supply chain in Italy, to assess the sustainability and circularity of five alternatives and outrank them. The results indicated that not all the alternatives are better in terms of supporting sustainable development and circular economy, compared to the baseline business model. In this supply chain, the extended lifetime for digestate from the aerobic digestion plant is the most 'sustainable and circular' alternative, while the capture of carbon dioxide from the same plant and its use for microalgae cultivation is the least 'sustainable and circular' alternative. A sensitivity analysis was conducted on different weighting sets during the assessment. It indicated that the priority of the decision makers can slightly change the outrank of the alternatives and the magnitude of the outranks.

1. Introduction

Sustainable development requires the balance of three aspects of the environment, economy, and society, while circularity is more related to two aspects of sustainable development, e.g. economic development and environmental sustainability. It is based on the

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principle that everything is "an input to another" [1]. The circular economy (CE) encourages the extension of product and material values, as well as minimizes waste generation and virgin resource use [2]. Sustainable development and circularity go in line and are vital for the future of our socio-economy.

The integration of CE principles into supply chains is increasingly recognized as critical for achieving sustainability, economic resilience, resource efficiency and creating a closed-loop supply chain (CLSC). According to Statista, the global circular economy market is projected to reach approximately USD 4.5 trillion by 2030, underscoring the growing importance of sustainable practices in supply chain management [3]. This substantial market growth reflects a broader industry shift towards resource optimization and waste reduction, driven by environmental and economic imperatives. The latest research highlights the significance of robust scenario-based probabilistic-stochastic programming to design CLSCs under hybrid uncertainty, where both probabilistic and imprecise data are considered [4]. This approach enhances supply chain resilience by addressing uncertainties in demand, supply, and process efficiency [5].

Additionally, recent studies by Refs. [6,7] emphasise incorporating advanced artificial intelligence (AI) techniques to predict and mitigate risks, further strengthening the robustness of supply chains. The convergence of AI with robust optimization models is pivotal in handling the complexities of real-world supply chains, where traditional models often fall short [8–10]. [10] highlight how digital technologies like digital twins, blockchain, and Internet of Thing (IoT) are transforming supply chain transparency and decision-making, making the integration of these technologies essential in modern supply chain design. This evolving landscape underscores the importance of studying CLSCs under hybrid uncertainty, providing both theoretical advancements and practical insights for industries striving to develop more sustainable and resilient supply chains.

In this context, bioenergy and biofuels are alternative energy sources, contributing to the mitigation of greenhouse gases, and fostering sustainable development and circular economy. The biomass-based energy supply chains (BSC) involve various processes such as growing and harvesting energy crops, transportation, pre-treatment, storage of feedstocks, production and generation of energy, and end-of-life treatment. A BSC with waste-free biorefineries utilizes all the available biomass components to make products and energy, consistent with the fundamental objective of a CE [11–13]. At the same time, maximizing biowaste utilization to produce biofuel will increase the economic value of the 'waste', and save the resources through recycling the 'waste', which promote CE [14]. Biomass feedstocks encompass diverse types and sources, and the energy conversion can employ various technologies like pyrolysis, anaerobic digestion, and hydrothermal methods [15–18]. Thus, any improvement during the life cycle stage of the BSC as well as the corresponding technology deployment may bring out the potential for fostering sustainable development and CE.

In the realm of sustainable development and energy projects, the application of multi-criteria decision-making (MCDM) methods is crucial yet often underutilized. MCDM techniques, including the Analytical Hierarchy Process, Technique for Order Performance by Similarity to Ideal Solution, and Analytic Network Process, are pivotal for evaluating complex decisions involving multiple, sometimes conflicting criteria. These methods enable comprehensive assessment by systematically comparing alternatives based on environmental, economic, and social dimensions [19–21]. Despite their established efficacy, there is a significant opportunity to enhance their application by integrating emerging technologies such as blockchain and IoT. Blockchain can improve transparency and efficiency in renewable energy supply chains, while IoT introduces new risk factors that require sophisticated decision frameworks [8,9,22,23]. Moreover, incorporating hybrid fuzzy decision approaches can address uncertainties and refine risk evaluations [24,25]. Thus, extending MCDM methods to encompass these innovations can offer a more robust and holistic framework for sustainable decision-making, addressing both technological advancements and practical implementation challenges in energy projects. However, due to the complexities involved in applying fuzzy techniques and emerging technologies like AI and IoT for companies within supply chains, this study focuses on the more established approach of combining MCDM with LCT to evaluate sustainable and circular options.

At the enterprise level, circular business models (CBMs) are the realization of the CE. They require companies to redesign their business strategies and models towards a higher resource efficiency and reducing the environmental burden from their economic activities. There are various types of CBMs according to different classifications. For example, the OECD (2015) classifies circular business models into five categories, including (1) circular supply models, (2) resource recovery models, (3) product life extension models, (4) sharing models, and (5) product service systems models [26]. Others categorize CBMs according to activities related to material flows and end-of-life treatment such as (1) repair and maintenance, (2) reuse and redistribution, (3) refurbishment and remanufacturing, (4) recycling, (5) cascading and repurposing and (6) organic feedstock [27].

In the biomass sector, several CBMs have been identified. According to Pavan et al., suitable CBMs for the BSC include recycling, cascading, repurposing, and organic feedstock models [28]. This study also proposed two CBMs with a centralized and a decentralized aerobic digestion plant. These models are applied to energy production from industrial waste. Other research emphasizes the application of CE principles, like recovery and recycling, to create closed-loop systems in BSC [29–31]. Allegue et al. suggested an integrated biorefinery for resource recovery and value-added product manufacturing. The study outlines several sustainability and circularity enhancement options based on these insights. For instance, thermal hydrolysis demonstrated a solid solubilization rate of up to 40.4 %, reducing disposal waste volume by 78.6 %. Furthermore, employing phototrophic treatment on the hydrolysate fostered biomass growth, characterized by a high protein content of 65 % by weight [29].

Some other studies suggested innovative technologies and practice that are applicable in the BSC to aim at sustaiablility and circularity. For example, the review of Crovella et al. showed that the carbon credit, or negative GHG emissions, at 37 kgCO$_2$eq, can be obtained by recovering the nutrients from agro-industrial wastewater to be used as soil amendment [32]. Moreover, it is identified that change in agricultural practice, e.g. organic agriculture, decreases energy consumption by 55 an% and GHG emissions by 65 %, compared to the conventional practice [33]. In several specific food chains, change in the manufacturing process of crude pea towards circularity helps to reduce 26 % of land requirement and other environmental impacts [34], or using biowaste and recovering wastewater in mushroom growing mitigates the GHG emissions and resource consumption [35].

Although several CBMs as well as sustainable development options are available, it is not simple for enterprises to select the most appropriate sustainability and circularity alternative. First, the sustainability and circularity indicators are large in quantity and complex in their nature [36]. Second, the selection of alternatives requires a comprehensive tool to cover all aspects of sustainability and circularity [37].

While significant advancements have been made in integrating CE principles and sustainability practices within supply chains, there remains a critical gap in the holistic assessment of sustainability and circularity using comprehensive decision-support tools. Current methodologies often fail to integrate both sustainability and circularity indicators effectively, with a predominant focus on either environmental or economic dimensions, leaving social aspects underexplored. This research addresses these gaps by developing an innovative decision-support system that merges Life Cycle Thinking (LCT) with advanced MCDM methods, incorporating state-of-the-art technologies and probabilistic-stochastic programming. This approach enables a more robust evaluation of sustainability and circularity, providing a comprehensive framework for decision-makers in the renewable energy sector. By filling these gaps, the research contributes to the advancement of sustainable supply chain management and offers actionable insights for both academia and industry, paving the way for more resilient and sustainable energy systems. Overall, this research advances the field by developing a comprehensive decision-support tool that integrates LCT and MCDM techniques. It provides practical solutions for balancing sustainability and technological innovation, thereby filling critical gaps in the current literature and offering actionable insights for policymakers, businesses, and researchers.

As a result, this paper fills in the practical and academic research gap to propose a tool for assessing the sustainability and circularity of the BSC. This tool is applied in a supply chain using rice straw for energy purposes, which will be used as an illustrative case study. Though the case study relates to the rice straw supply chain, the tool in fact is applicable for any other BSCs, for examples olive oil, tomato, etc. Five alternatives of the rice straw supply chain have been assessed and ranked, using the sustainability and circularity index. In the following sections, the tool and its application to assess the sustainability and circularity of a particular rice straw supply chain in Italy will be described in detail.

2. Tool for sustainability and circularity assessment

This study follows a four-step logical framework for developing the tool for assessing the sustainability and circularity of the BSC, combining MCDM techniques with LCT (as illustrated in Fig. 1).

First, the sustainability and circularity indicators are screened and selected by conducting a systematic literature review. Sustainability and circularity indicators are fundamental for evaluating the environmental, economic, and social impacts of supply chains. Sustainability encompasses three dimensions: environmental, economic, and social, while circularity focuses on resource efficiency and waste reduction. Indicators are selected based on a comprehensive review of the literature, ensuring they align with these principles and capture relevant aspects of both sustainability and circularity. Moreover, this step involves the classification of indicators into sub-groups for identifying specific equations and calculating impacts, which correspond to the selected indicators. The indicators are categorized to provide a clear framework for assessment, ensuring that the tool is both comprehensive and applicable to various supply chain contexts.

In step 2, the impacts are identified equation and calculated value by applying LCT approaches such as life cycle assessment, life cycle costing, social life cycle assessment, and material flow analysis. LCT provides a holistic perspective on the impacts of products and processes across their entire lifecycle. It offers a detailed evaluation of the environmental, economic, and social dimensions from raw material extraction through to end-of-life disposal, providing a thorough understanding of the sustainability impacts associated

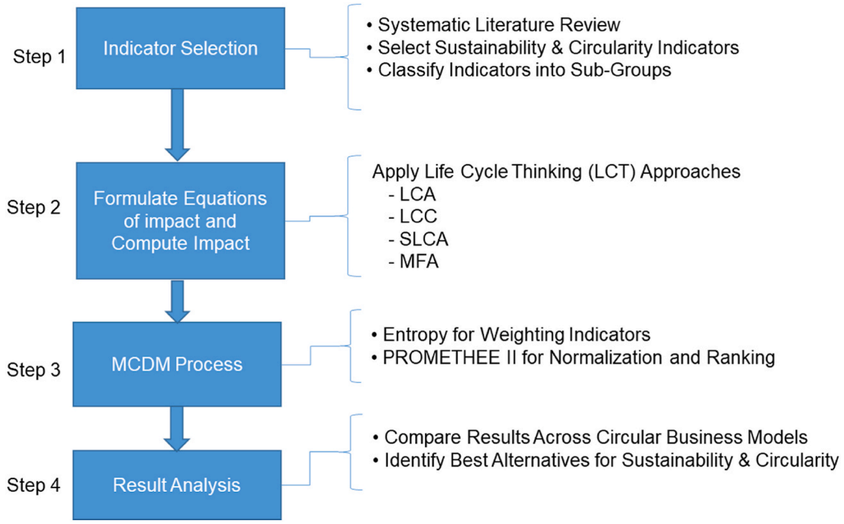


Fig. 1. Framework for sustainability and circularity assessment in biomass supply chains.

with each business model.

Step 3 relates to the MCDM process, which is essential for evaluating complex decisions involving multiple, often conflicting criteria. The Entropy [38] is applied for weighting each indicator, reflecting its importance in the overall assessment. The PROMETHEE II [38] is then used to normalize the impacts and rank the alternatives. This process facilitates a structured comparison of different circular business models, highlighting the most effective options for enhancing sustainability and circularity.

The last step is to obtain the sustainability and circularity results and to compare these obtained results among several alternative circular business models. This comparative analysis helps to identify the best alternatives for improving resource efficiency and reducing waste. The tool's effectiveness is illustrated through a case study of the rice straw supply chain in Italy, demonstrating its practical application and providing practical insights for stakeholders. The detail of each step is elaborated in the following sections.

2.1. Sustainability and circularity indicators

49 sustainability and circularity indicators have been selected in this study [36]. The selection of sustainability and circularity indicators was conducted through a systematic literature review, which allowed for the identification of the most relevant and widely recognized indicators across environmental, economic, and social dimensions. The sustainability indicators were collected from

Table 1
Selected circularity and sustainability indicators.

Group of Indicator	Indicator
Environmental quality	Global warming potential (kgCO_2eq)
	Particulate matter formation (kg$PM_{2.5}$eq)
	Ozone depletion (kg CFC-11 eq)
	Ionising radiation human health (kBq U-235 eq)
	Ionising radiation ecosystem (CTUe)
	Photochemical ozone formation (kg NOx eq)
	Acidification (kg SO_2 eq)
	Eutrophication, marine (kg N eq)
	Eutrophication, freshwater (kg P eq)
	Eutrophication, terrestrial (mol N eq)
	Ecotoxicity, marine (kg 1,4-DCB)
	Ecotoxicity, freshwater (kg 1,4-DCB)
	Human toxicity, non-cancer (kg 1,4-DCB)
	Human toxicity, cancer (kg 1,4-DCB)
Resource depletion	Primary energy consumption (MJ)
	Primary renewable energy shares in the total primary energy consumption (%)
	Abiotic depletion potential (kg Sb eq)
	Land use (m^2a)
	Water consumption (m^3)
Social sustainability	Proportion of employment with education and training out of total employment (%)
	Proportion of women in managerial positions (%)
	Proportion of informal employment in total employment (%)
	Fair Salary (dimensionless)
	Child Labour (risk hour)
	Fatal and non-fatal occupational injuries (cases)
	Research and development expenditure as a proportion of revenue (euro)
	Social investment (euro)
	Number of healthy workers in total employments (person)
	Forced labour (person)
	Local employment (person)
	Job creation (man year)
	Income generated by jobs (euro)
	Working hours (hour)
	Employee participation in the circular model (person)
Economic sustainability	Total cost (euro)
	Revenue (euro)
	Net Present Value (euro)
	Internal Rate of Return (%)
	Circular investment (euro)
Circularity	Self-sufficiency of raw materials (%)
	Generation of waste (ton)
	Percentage of recycling rate out of all waste (%)
	Percentage of recycling rate of plastic waste out of total waste (%)
	Percentage of recycling rate of paper and paperboard out of total waste (%)
	Circular material use rate (%)
	Proportion of material losses in primary material (%)
	Use of critical materials for producing one unit of product (ton/unit product)
	Reuse manufacturing process (ton)
	Food waste (ton)

sustainable development goals [39], life cycle environmental impact assessment methods such as ReCiPe [40], guidelines for social life cycle assessment of the United Nations Environmental Program [41], and other literatures [40,42–50]. Besides, the circularity indicators were gathered from the circular economy indicator set of the European Commission [51] and other literature [52–54]. This approach ensures that the indicators used in the study are not only credible and well-supported in established research but also reflect the latest advancements and best practices in the field.

The inclusion criteria for these indicators were based on their ability to capture critical aspects of sustainability and circularity within BSC, such as resource efficiency, waste minimization, greenhouse gas emissions, and economic viability. By categorizing the indicators into sub-groups, the study ensures that all relevant dimensions of sustainability and circularity are comprehensively covered, providing a holistic assessment framework. These indicators are classified into five groups, including:

- 14 environmental quality indicators,
- 5 resource depletion indicators,
- 15 social indicators,
- 5 economic indicators, and
- 10 circularity indicators.

The list of indicators are presented in Table 1.

2.2. *Impact calculation*

To calculate the sustainability and circularity impacts with the 49 indicators listed, LCT approaches have been applied. Furthermore, the specific equations for calculating the impacts corresponding to these indicators were chosen based on their relevance to the biomass sector and their ability to accurately quantify the outcomes of various supply chain activities. The application of LCT methodologies, such as Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (SLCA), is justified by their ability to provide a comprehensive evaluation of the environmental, economic, and social impacts associated with different stages of the supply chain. Specifically, life cycle assessment was applied to calculate environmental quality and resource depletion indicators [43,55–57]. At the same time, social life cycle assessment and life cycle costing were used to quantify social and economic indicators, respectively [26,41,45,47,54,58–70]. Material flow analysis was used for calculating the circularity indicators [52,54,64]. The specific equations for calculating sustainability and circularity impacts can be found in Ref. [36].

2.3. *Weighting and normalization*

The weighting of the sustainability and circularity impacts of all alternatives were done by applying the Entropy method. Entropy is a useful multi-criteria technique for evaluating and making decisions involving multiple factors. This method was developed based on information entropy principle and can be used to measure the uncertainty (or variability) of information [71]. One strength of this method is that it allows to determine the criteria weights without decision-makers intervention [72–76].

The use of the entropy method for weighting the impacts and the PROMETHEE II method for normalising them is justified by their effectiveness in dealing with complex decision-making scenarios involving multiple criteria. The entropy method is particularly suitable for assigning objective weights to indicators based on the variability of the data. At the same time, PROMETHEE II provides a robust framework for ranking alternatives based on their performance across different criteria. These methods are well-suited to handle the trade-offs and uncertainties characteristic of biomass supply chains, thereby enhancing the reliability and validity of the assessment results.

The calculation process for determining the criteria weights starts with the standardization of measured impacts (equation (1)), followed by the definition of the entropy value (equation (2)) and ending with the quantification of weights (equation (3)).

$$s_{ij} = X_{ij} \Bigg/ \sum_{i=1}^{m} (X_{ij}) \tag{1}$$

$$E_j = -(\ln(\mathrm{m}))^{-1} \sum_{i=1}^{m} s_{ij} \ln\left(\mathrm{p}_{ij}\right) \tag{2}$$

$$w_j = (1 - E_j) \Bigg/ \left(\mathrm{n} - \sum_{j=1}^{n} \mathrm{E}_j\right) \tag{3}$$

In which:

s_{ij} is the standard value of alternative i, impacts j
X_{ij} is the quantified value of alternative i, impact j (obtained in Step 2)
m is the total number of alternatives
n is the total number of impacts (49 impacts, in this study)
E_j is the entropy value of impact j

w_j is the weight of impact j

The normalization of impacts aims at obtaining the difference between the same impacts of different alternatives. This difference indicates how the quantified impacts of one alternative is better (or worse) than the corresponsing impacts of other alternatives, which will be called as preference value. First, the quantified impacts of each alternative were normalized to the range from 0 to 1 (equations (4) and (5)). Then, the preference value between two alternatives is compared for each impact (equations (6) and (7)) [77].

$$\mathrm{R_{ij}} = \frac{X_{ij} - X_{ijmin}}{X_{ijmax} - X_{ij\ min}} \text{ If impact j is positive.} \tag{4}$$

$$\mathrm{R_{ij}} = \frac{X_{ijmax} - X_{ij}}{X_{ijmax} - X_{ij\ min}} \text{ If impact j is negative.} \tag{5}$$

$$dj_{(i1,i2)} = rj_{i1} - rj_{i2} \tag{6}$$

$$pj_{(i1,i2)} = \mathrm{F}\left(dj_{(i1,i2)}\right) \text{ with } \forall \mathrm{x} \in [-\infty, \infty], 0 \le \mathrm{F(x)} \le 1 \tag{7}$$

In which:

$\mathrm{R_{ij}}$ is the normalized value of alternative i, impact j

r is the element of matrix R, rj_{i1} is the value for impact j alternative $i1$, rj_{i2} is the value for impact j alternative $i2$.

$dj_{(i1,i2)}$ is the difference between alternative $i1$ and $i2$ for impact j

$pj_{(i1,i2)}$ is the preference value for impact j between two alternatives $i1$ and $i2$.

F is the preference function. There are six preference funtions including usual, U-shaped, V-shaped, level, linear and Guassian. In the case study, the usual function was applied.

2.4. Outranking results

In step 4, the outranking results are obtained by aggregating all impacts (equation (8)) and comparing (or outranking) them by each pair of alternatives (equations (9)–(11)). The higher the value of the net outranking flow for the alternative, the better the alternative is (compared to the remaining alternatives).

$$\pi(i1, i2) = \sum_{j=1}^{n} w_j \times pj_{(i1,i2)} \tag{8}$$

$$\varphi^{+}_{(i)} = \frac{1}{n-1} \sum_{j=1}^{n} \pi(i1, i2) \tag{9}$$

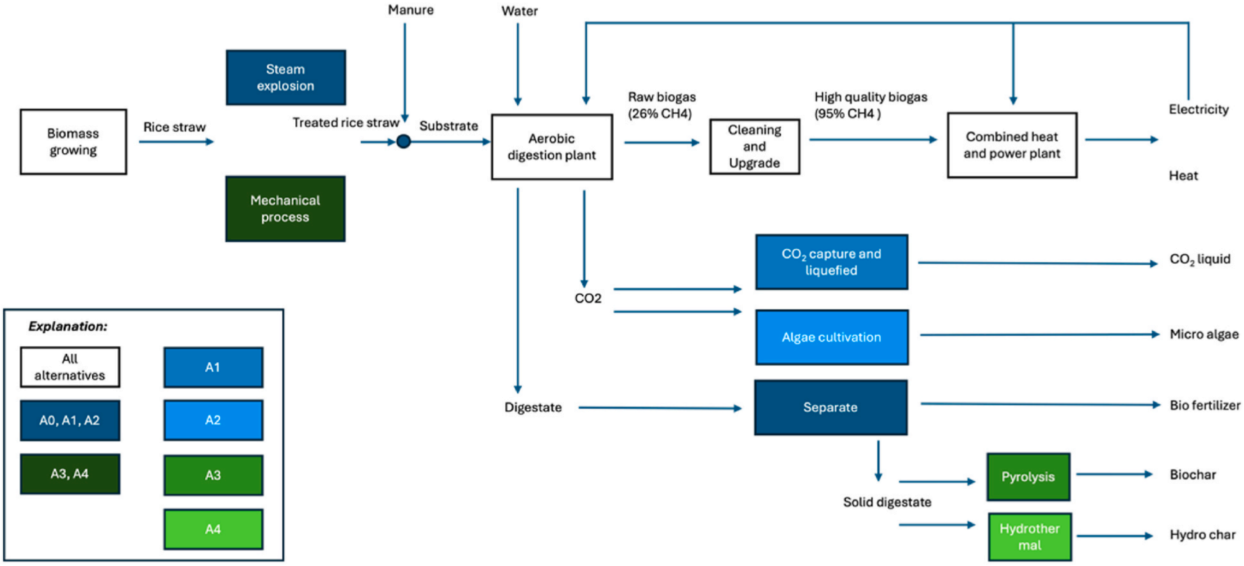


Fig. 2. Five alternatives of the rice straw supply chain.

$$\varphi^-_{(i)} = \frac{1}{n-1}\sum_{j=1}^{n}\pi(i2, i1) \tag{10}$$

$$\varphi_{(i)} = \varphi^+_{(i)} - \varphi^-_{(i)} \tag{11}$$

In which:

$\pi(i1, i2)$ is the outrank between alternative $i1$ and $i2$, aggregated for all impacts

$\varphi^+_{(i)}$ and $\varphi^-_{(i)}$ are the positive and negative outranking flow of alternative i

$\varphi_{(i)}$ is the net outranking flow of alternative i

For further supporting the decision-making process, all the calculations were written on Matlab. This facilitated the collection and importing of data as well as enabled the monitoring and storage of the obtained results. The resulting tool was applied to rice straw supply chain to verify its contribution to support the decision making process.

3. Case study on the rice straw supply chain

3.1. Description of five alternatives

In this paper, the rice straw supply chain for generating electricity and heat in Pavia, Italy was selected as a case study. Five alternatives were assessed in this paper, as illustrated in Fig. 2. In the business-as-usual case (A0), 6000 tonnes of rice straw are obtained as a co-product of the biomass growing process. This rice straw is pre-treated by steam explosion to reduce the proportion of total solids out of biomass feedstock from 91.4 % to 37.8 %, and consequently increase the energy productivity of the next process. The treated rice straw is then transported for 2.1 km to an anaerobic digestion (AD) plant. In the AD plant, treated rice straw is mixed with manure and water, creating a slurry substrate (at 15 % of total solids) for feeding the digester and generating raw biogas. The AD plant consumes 18 tonnes of straw daily, equivalent to 6 thousand tonnes per year. The AD plant operates around 8000 h/year, within 20 years of lifetime. For each tonne of rice straw, the AD plant can generate 450 m^3 of raw biogas with 26 vol percent (%v/v) of methane. The raw biogas from the AD plant is then cleaned to reach the natural gas (NG) quality. After cleaning, the NG-quality biogas is used to produce electricity and heat at the combined heat and power (CHP) plant. The CHP plant has an installed capacity of 1500 kW, with efficiency of 88.8 %, and generates 37 % of electricity and 51.8 % of heat. The generated electricity is self-used in the CHP plant, transmitted to the AD plant, and supplied to the local grid.

Another co-product of AD plant is digestate, which is extracted from the bottom of the digester using a centrifugal shredder pump. The digestate is sent to a separator, where the solid fraction (15 %) is separated from the liquid one (85 %). Both fractions of the digestate are stored in open concrete tanks and are used as a bio-fertilizer.

In other alternative situations (A1, A2, A3, and A4), CBMs are applied during the rice straw supply chain to improve the sustainability and circularity of the supply chain. In the A1 alternative, carbon dioxide (CO_2) from the AD plant, instead of being emitted into the environment, is captured and liquefied for sale in the market. In this alternative, the upgrading process is added to the treatment of raw biogas. CO_2 is separated and collected, then converted into liquid CO_2, and methane is supplied to the CHP plant. The A2 alternative is similar to the A1 one, but CO_2 from the upgrading stage and liquid digestate from the separator are used to cultivate microalgae. The cultivated microalgae are harvested, partially dried, and post-treated as animal feed. The A1 and A2 alternatives are presented in blue color, with different shade in Fig. 2 to show their similarity.

In the A3 and A4 alternatives (presented in green color in Fig. 2), the harvested rice straws go through a mechanical process, instead of using steam explosion. During the mechanical process, the rice straw is cut into small pieces, with the mix of water. The application of mechanical process reduces the amount of generated raw biogas in the AD plant to 380 m^3 of raw biogas per tonne of rice straw. Besides, other CBMs are also applied for digestate treatment. In the A3 alternative, the solid digestate is used as feedstock for a pyrolysis process to produce biochar. Meanwhile, in A4 alternative, the solid digestate from AD plant is used as feedstock for hydrothermal carbonization process for producing hydrochar. Both biochar and hydrochar are sold on the market.

3.2. Eco-profiles of five alternatives

The eco-profiles of five alternatives within the rice straw supply chain are presented in Table 2. In the table, the red color indicates the less sustainable and circular of the alternatives. The color gradually changes into yellow if the alternative is more sustainable and circular. In general, the A2 alternative is worse in terms of environmental sustainability, but better in social and economic sustainability and circularity. The A0, A1, A3, and A4 alternatives, are better in terms of environmental sustainability such as environmental quality and resource depletion. However, they are worse in terms of social and economic sustainability and circularity, especially in the cases of A0 and A1 alternatives.

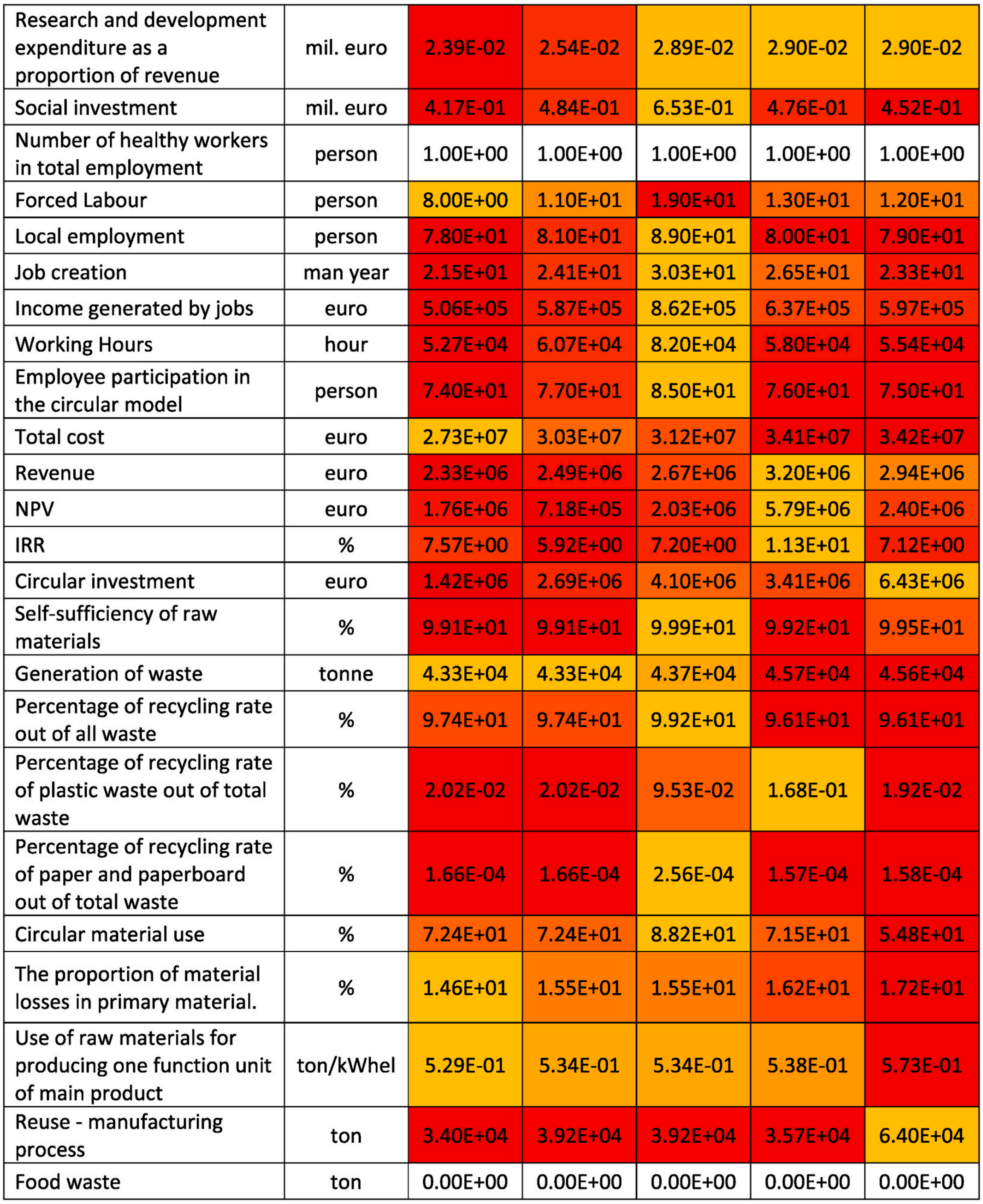
There is not much difference among environmental quality impacts of the A0, A1, A3, and A4 alternatives, however, these impacts are much higher in the A2 alternative, especially for global warming potential (GWP), particulate matter formation (PMF), acidification, ecotoxicity and human toxicity, cancer. For example, the GWP and PMF of the A2 alternative is 37 times and 60 times higher than the average, corresponding impacts of the four remaining alternatives. Besides, the human toxicity, cancer of the A2 alternative is even 121 times higher than that of the four remaining alternatives. The significant increase in the impacts of A2 is due to the extension of the rice straw supply chain to cover various stages of microalgae cultivation and harvesting.

It should be noted that in this study, the impacts are considered for the supply chain. The system boundaries of the supply chain in these alternatives are different, and being considerably extended in the A2 alternative, compared to the remaining alternatives. Considering that microalgae in the A2 alternative can be used as animal feed and will replace other animal feed, the human toxicity and other environmental impacts of the A2 alternative will centainly reduce, if the system boundary are narrowed. In this present study, the extended system boundary in the A2 alternative causes the significant impacts in some environmental impact categories,

Table 2

Eco-profiles of five alternatives within the rice straw supply chain.

Impacts	Unit	A0	A1	A2	A3	A4
Global warming potential	kg CO_2 eq	1.48E+06	1.20E+06	5.57E+07	1.68E+06	1.57E+06
Particulate matter	kg PM2.5 eq	1.79E+03	1.81E+03	1.09E+05	1.85E+03	1.72E+03
Ozone depletion	kg CFC11 eq	1.59E+01	1.58E+01	6.47E+01	1.71E+01	1.49E+01
Ionising radiation human health	kBq U235 eq	9.94E+05	9.94E+05	1.59E+06	9.99E+05	9.99E+05
Ionising radiation ecosystem	CTUe	1.77E-01	1.77E-01	2.69E-01	1.95E-01	1.95E-01
Photochemical ozone formation	kg NOx eq	1.25E+05	1.25E+05	2.02E+05	1.26E+05	1.25E+05
Acidification	kg SO_2 eq	9.66E+03	9.83E+03	5.69E+05	1.05E+04	9.74E+03
Eutrophication, marine	kg N eq	9.94E+02	1.02E+03	1.87E+04	1.12E+03	1.03E+03
Eutrophication, freshwater	kg P eq	5.86E+02	5.86E+02	1.14E+04	6.16E+02	6.16E+02
Eutrophication, terrestrial	mol N eq	1.13E+05	1.14E+05	1.56E+06	1.15E+05	1.08E+05
Ecotoxicity, marine	kg 1.4 DCB	4.52E+04	4.61E+04	1.55E+06	4.51E+04	4.50E+04
Ecotoxicity, freshwater	kg 1.4 DCB	3.61E+04	3.61E+04	1.08E+06	3.69E+04	3.69E+04
Human toxicity, non-cancer	kg 1.4 DCB	1.04E+07	1.04E+07	4.24E+07	1.13E+07	1.13E+07
Human toxicity, cancer	kg 1.4 DCB	1.82E+03	1.82E+03	2.60E+06	5.24E+04	2.98E+04
Primary energy consumption	MJ	1.40E+07	1.83E+07	1.96E+07	1.66E+07	1.25E+07
Primary renewable energy consumption sharing	%	4.96E+01	6.16E+01	6.44E+01	5.85E+01	4.38E+01
Abiotic depletion potential	kg Sb eq	2.22E+04	2.22E+04	2.32E+04	2.22E+04	2.22E+04
Land use	m^2a	5.11E+04	5.11E+04	1.78E+05	6.91E+04	5.11E+04
Water consumption	m^3	4.07E+06	4.07E+06	7.11E+06	4.07E+06	4.10E+06
The proportion of employees with education and training out of total employment	%	2.18E+01	2.47E+01	3.15E+01	2.75E+01	2.79E+01
The proportion of women in managerial positions of total employment	%	1.41E+01	1.36E+01	1.35E+01	1.50E+01	1.52E+01
The proportion of informal employment in total employment	%	8.21E+01	7.90E+01	7.19E+01	8.00E+01	8.10E+01
Fair Salary	times	1.07E+00	1.07E+00	1.17E+00	1.22E+00	1.20E+00
Child Labour	risk hour	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Fatal and non-fatal occupational injuries	case	5.60E+00	6.76E+00	9.84E+00	7.53E+00	7.14E+00



Research and development expenditure as a proportion of revenue	mil. euro	2.39E-02	2.54E-02	2.89E-02	2.90E-02	2.90E-02
Social investment	mil. euro	4.17E-01	4.84E-01	6.53E-01	4.76E-01	4.52E-01
Number of healthy workers in total employment	person	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
Forced Labour	person	8.00E+00	1.10E+01	1.90E+01	1.30E+01	1.20E+01
Local employment	person	7.80E+01	8.10E+01	8.90E+01	8.00E+01	7.90E+01
Job creation	man year	2.15E+01	2.41E+01	3.03E+01	2.65E+01	2.33E+01
Income generated by jobs	euro	5.06E+05	5.87E+05	8.62E+05	6.37E+05	5.97E+05
Working Hours	hour	5.27E+04	6.07E+04	8.20E+04	5.80E+04	5.54E+04
Employee participation in the circular model	person	7.40E+01	7.70E+01	8.50E+01	7.60E+01	7.50E+01
Total cost	euro	2.73E+07	3.03E+07	3.12E+07	3.41E+07	3.42E+07
Revenue	euro	2.33E+06	2.49E+06	2.67E+06	3.20E+06	2.94E+06
NPV	euro	1.76E+06	7.18E+05	2.03E+06	5.79E+06	2.40E+06
IRR	%	7.57E+00	5.92E+00	7.20E+00	1.13E+01	7.12E+00
Circular investment	euro	1.42E+06	2.69E+06	4.10E+06	3.41E+06	6.43E+06
Self-sufficiency of raw materials	%	9.91E+01	9.91E+01	9.99E+01	9.92E+01	9.95E+01
Generation of waste	tonne	4.33E+04	4.33E+04	4.37E+04	4.57E+04	4.56E+04
Percentage of recycling rate out of all waste	%	9.74E+01	9.74E+01	9.92E+01	9.61E+01	9.61E+01
Percentage of recycling rate of plastic waste out of total waste	%	2.02E-02	2.02E-02	9.53E-02	1.68E-01	1.92E-02
Percentage of recycling rate of paper and paperboard out of total waste	%	1.66E-04	1.66E-04	2.56E-04	1.57E-04	1.58E-04
Circular material use	%	7.24E+01	7.24E+01	8.82E+01	7.15E+01	5.48E+01
The proportion of material losses in primary material.	%	1.46E+01	1.55E+01	1.55E+01	1.62E+01	1.72E+01
Use of raw materials for producing one function unit of main product	ton/kWhel	5.29E-01	5.34E-01	5.34E-01	5.38E-01	5.73E-01
Reuse - manufacturing process	ton	3.40E+04	3.92E+04	3.92E+04	3.57E+04	6.40E+04
Food waste	ton	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

however, brings other social and economic benefits which will be futher discussed in the following sections.

Regarding other sustainability and circularity impacts, such as resource depletion, social sustainability, economic sustainability, and circularity, there is not much difference among the five alternatives, indicated by the inconsiderable difference between the mean and average impacts of the five alternatives.

Table 3 presents the difference between the environmental quality impacts of the A2 alternative and the four remaining alternatives, and Table 4 presents the median and average values of five alternatives in resource depletion, social sustainability, economic sustainability and circularity.

3.3. Normalization results

The results of 49 impacts are normalized and aggregated into five groups of sustainability and circularity index: Environmental quality, Resource depletion, Social sustainability, Economic sustainability, and Circularity. Fig. 3 illustrates the normalization results of five alternatives. The environmental quality index of the five alternatives ranges from 0 to 13.9, while the range of resource depletion and economic sustainability is between 1 and 4.1. The high end of the environmental quality index is due to the large number of indicators, 14 indicators, compared to 5 indicators each for resource depletion and economic sustainability. This is correspondingly correct for social sustainability and circularity, with the highest value of 9.3 and 8 due to the relatively large numbers of assessed indicators, at 14 and 11, respectively.

As it can be expected from the eco-profiles of the five alternatives, there is not much difference in the normalization results of the A0, A1, A3, and A4 alternatives. These alternatives have the same pattern of highest environmental quality index, at around 13.8, and being followed by Social sustainability at around 6.6, and Resource depletion, at around 4. The Economic sustainability of these four alternatives ranges between 1.8 and 4.3, and Circularity is from 2.5 to 5.

Meanwhile, the normalization results of the alternative A2 have a distinctive pattern, with the highest values of Social sustainability and Circularity, at around 9 and 8, respectively. The Environmental quality index of this alternative is 0, meaning that this alternative has the highest impact on environmental quality for all indicators. Similarly, this alternative has the highest impact on most resource depletion indicators, with a normalized value of 1. The Economic sustainability index of this alternative is 2.8, which is in the range of the four remaining alternatives.

3.4. Weighting sets for different priority

In this paper, apart from the weighting set obtained from the Entropy method without any priority, two additional weighting sets are obtained. The first weighting set gives equal priority to the five indices of environmental quality, resource depletion, social sustainability, economic sustainability, and circularity, at 0.2 each. The second weighting set considers the biomass supply chain in the context of climate change and the risk of material shortage, which requires taking action in resource efficiency, reuse and recycling of materials, etc. As a consequence, a higher weight is set on the circularity index, at 0.3. The weights of environmental quality, resource depletion, social sustainability, and economic sustainability are 0.15, 0.2, 0.15, and 0.2, respectively. The specific weights for each indicator are presented in Table 5.

3.5. Outranking results and sensitivity analysis

The outranking results indicate that A3 is the best alternative in the overall sustainability and circularity impacts. Meanwhile, A2 is the worst alternative in terms of sustainability and circularity. There is not much difference among the A0, A1, and A4 alternatives, and the outranking order is A3>A4>A0>A1>A2. This outranking order is obtained with a non-prioritized weighting set, meaning the weighting set is completely objective, achieved by applying the Entropy method, and being independent of decision makers' expectations.

In the case of the different weighting sets that were also applied, the outranking order slightly changes into A3>A4>A1>A0>A2, for both cases of equal weights and circularity-oriented weights. Fig. 4 illustrates the outranking orders of five alternatives with different weighting sets.

Although the ranking order slightly changes, in the order of A0 and A1, the magnitude of change is completely different when three weighting sets are applied. The specific outranking results with different weighting sets are presented in Table 6. With the application of the non-prioritized weighting set, the A2 alternative is outstandingly worse than the remaining alternatives, at −0.88 compared to around 0.22 of the other four alternatives. However, if the equal weights or circularity-oriented weights are used, the absolute difference among the five alternatives is reduced. Specifically, the outranking result of the A2 alternative is about −0.23, compared to

Table 3
Difference between the environmental sustainability of A2 and the four remaining alternatives.

Impacts	A2	A0-1, A3-4, average	Difference
Global warming potential	5.57E+07	1.48E+06	37.52
Particulate matter formation	1.09E+05	1.79E+03	60.78
Ozone depletion	6.47E+01	1.59E+01	4.07
Ionising radiation human health	1.59E+06	9.97E+05	1.59
Ionising radiation ecosystem	2.69E-01	1.86E-01	1.44
Photochemical ozone formation	2.02E+05	1.25E+05	1.62
Acidification	5.69E+05	9.94E+03	57.25
Eutrophication, marine	1.87E+04	1.04E+03	17.99
Eutrophication, freshwater	1.14E+04	6.01E+02	18.89
Eutrophication, terrestrial	1.56E+06	1.13E+05	13.88
Ecotoxicity, marine	1.55E+06	4.54E+04	34.10
Ecotoxicity, freshwater	1.08E+06	3.65E+04	29.66
Human toxicity, non-cancer	4.24E+07	1.08E+07	3.91
Human toxicity, cancer	2.60E+06	2.15E+04	121.25

Table 4
Mean and average value of resource depletion, social sustainability, economic sustainability and circularity of five alternatives.

Impacts	Mean	Average
Energy consumption	1.66E+07	1.62E+07
Renewable energy consumption sharing	5.85E+01	5.56E+01
Abiotic depletion potential	2.22E+04	2.24E+04
Land use	5.11E+04	8.00E+04
Water consumption	4.07E+06	4.69E+06
The proportion of employees with education and training out of total employment	2.75E+01	2.67E+01
The proportion of women in managerial positions of total employment	1.41E+01	1.43E+01
The proportion of informal employment in total employment	8.00E+01	7.88E+01
Fair salary	1.17E+00	1.15E+00
Child labour	0.00E+00	0.00E+00
Fatal and non-fatal occupational injuries	7.14E+00	7.37E+00
Research and development expenditure as a proportion of revenue	2.89E-02	2.72E-02
Social investment	4.76E-01	4.96E-01
Number of healthy workers in total employment	1.00E+00	1.00E+00
Forced Labour	1.20E+01	1.26E+01
Local employment	8.00E+01	8.14E+01
Job creation	2.41E+01	2.51E+01
Income generated by jobs	5.97E+05	6.37E+05
Working hours	5.80E+04	6.17E+04
Total cost	3.12E+07	3.14E+07
Revenue	2.67E+06	2.73E+06
NPV	2.03E+06	2.54E+06
IRR	7.20E+00	7.83E+00
Circular investment	3.41E+06	3.61E+06
Employee participation in the circular model	7.60E+01	7.74E+01
Self-sufficiency of raw materials	9.92E+01	9.94E+01
Generation of waste	4.37E+04	4.43E+04
Percentage of recycling rate out of all waste	9.74E+01	9.72E+01
Percentage of recycling rate of plastic waste out of total waste	2.02E-02	6.45E-02
Percentage of recycling rate of paper and paperboard out of total waste	1.66E-04	1.81E-04
Circular material use	7.24E+01	7.19E+01
The proportion of material losses in primary material.	1.55E+01	1.58E+01
Use of raw materials for producing one function unit of main product	5.34E-01	5.42E-01
Reuse - manufacturing process	3.92E+04	4.24E+04
Food waste	0.00E+00	0.00E+00

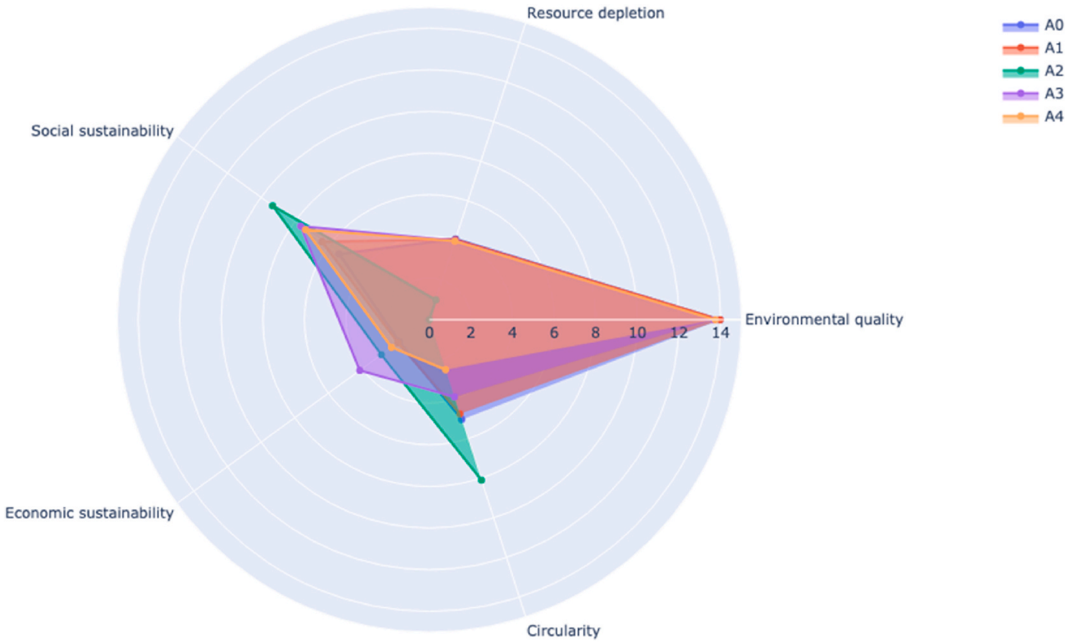


Fig. 3. Normalization results of five alternatives.

Table 5
Weighting sets.

Indicator	Equal weights	Material-oriented weights
Global warming potential	0.022	0.017
Particulate matter formation	0.025	0.019
Ozone depletion	0.004	0.003
Ionising radiation human health	0.000	0.000
Ionising radiation ecosystem	0.000	0.000
Photochemical ozone formation	0.000	0.000
Acidification	0.024	0.018
Eutrophication, marine	0.017	0.013
Eutrophication, freshwater	0.017	0.013
Eutrophication, terrestrial	0.015	0.011
Ecotoxicity, marine	0.022	0.016
Ecotoxicity, freshwater	0.021	0.016
Human toxicity, non-cancer	0.004	0.003
Human toxicity, cancer	0.028	0.021
Environmental quality	**0.200**	**0.150**
Energy consumption	0.013	0.013
Renewable energy consumption sharing	0.009	0.009
Abiotic depletion potential	0.000	0.000
Land use	0.149	0.149
Water consumption	0.029	0.029
Resource depletion	**0.200**	**0.200**
The proportion of employees with education and training out of total employment	0.012	0.009
The proportion of women in managerial positions of total employment	0.002	0.001
The proportion of informal employment in total employment	0.002	0.001
Fair salary	0.002	0.002
Child labour	0.000	0.000
Fatal and non-fatal occupational injuries (case)	0.028	0.021
Research and development expenditure as a proportion of revenue	0.005	0.004
Social investment	0.021	0.016
Number of healthy workers in total employment	0.000	0.000
Forced labour	0.064	0.048
Local employment	0.002	0.001
Job creation	0.012	0.009
Income generated by jobs	0.027	0.020
Working hours	0.022	0.016
Employee participation in the circular model	0.002	0.002
Social sustainability	**0.200**	**0.150**
Total cost	0.002	0.002
Revenue	0.004	0.004
NPV	0.119	0.119
IRR	0.015	0.015
Circular investment	0.061	0.061
Economic sustainability	**0.200**	**0.200**
Self-sufficiency of raw materials	0.000	0.000
Generation of waste	0.000	0.000
Percentage of recycling rate out of all waste	0.000	0.000
Percentage of recycling rate of plastic waste out of total waste	0.172	0.258
Percentage of recycling rate of paper and paperboard out of total waste	0.009	0.013
Circular material use	0.005	0.007
The proportion of material losses in primary material.	0.001	0.001
Use of raw materials for producing one function unit of main product	0.000	0.000
Reuse - manufacturing process	0.013	0.020
Food waste	0.000	0.000
Circularity	**0.200**	**0.300**

about 0.35 of the best alternative (A3).

There are several implications for these outranking results. First, not all the CBMs are better than the baseline model, when comprehensively considering all aspects of sustainability and circularity. It is proved by the fact that the A0 alternative is not always the worst one. The application of CBMs, such as capturing and using CO_2 for cultivating microalgae in the A2 alternative, aims to extend the life cycle of waste, and convert it into an input for the next process. However, this CBM causes more negative impacts on sustainable development and circular economy than ‘do nothing’ as in the A0 situation.

It is impossible to deny that most CBMs are more sustainable and have a higher circular ability than the baseline situation. This is indicated by the fact that most of the proposed CBMs, for example using digestate to produce biochar and hydrochar in the A3 and A4 alternatives proves to be much better than the A0 alternative. Therefore, it is certain that the sustainability and circularity of CBMs need to be assessed case by case, and in the context of a specific supply chain.

Second, the application of this sustainability and circularity assessment tool is suitable for BSC. It identifies the sustainability and

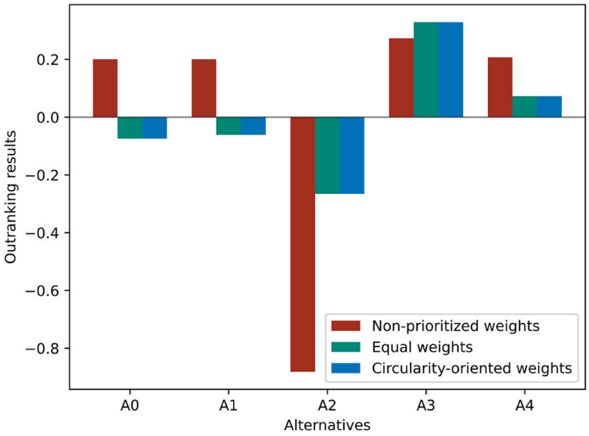


Fig. 4. Comparison of outranking order among alternatives and weighting sets.

Table 6
Outranking results with different weighting sets.

Alternative	Non-prioritized weights	Equal weights	Circularity-oriented weights
A0	0.200577	-0.0744718	-0.1097832
A1	0.200559	-0.0614621	-0.1030737
A2	-0.88156	-0.2656832	-0.2046686
A3	0.273346	0.32905789	0.38631073
A4	0.207079	0.07255927	0.03121474

circularity impacts of the BSC and compares various CBMs applied within the BSC. Moreover, it ranks these potential CBMs less subjectively, being independent from the decision makers, considering both positive and negative impacts of CBMs on the different aspects of sustainability and circularity such as environmental quality, resource depletion, social and economic benefits, recyclability, etc.

Furthermore, the sensitivity analysis which is conducted on several weighting sets, suggests that the tool can be used with more decision-makers' control. When priority is (partly) subjectively set on equal weights among sustainability and circularity index, or circularity-oriented weights, the outranking order of various CBMs slightly changes, as well as the magnitude of the outranking order. In these cases, the tool proves itself as being scientific-based, while practical by taking into account the users' preferences.

In summary, the application of the decision support tool to the rice straw supply chain provided valuable insights into the performance of different CBMs across various sustainability and circularity indicators. The five assessed alternatives were ranked based on their overall sustainability and circularity scores, calculated using a combination of LCA, LCC, SLCA, and material flow analysis. The environmental analysis revealed that alternatives utilizing anaerobic digestion for bioenergy production reduces greenhouse gas emissions and improving resource efficiency, showcasing the potential of converting agricultural waste into valuable energy with a minimized carbon footprint. The economic analysis indicated that alternatives embracing circular practices, such as recycling and resource recovery, offered superior cost-effectiveness in the long term, driven by reduced waste disposal costs and by-product reuse. Regarding social dimension, alternatives promoting local employment and community engagement achieved higher social sustainability scores, indicating the importance of integrating social aspects into sustainability assessments, especially in rural areas. Finally, the circularity assessment demonstrated that alternatives closing material loops and fully utilizing all components of rice straw, such as through biochar production, were most effective in advancing circular economy principles and enhancing long-term agricultural sustainability.

4. Discussion

Implementing a comprehensive tool for assessing sustainability and circularity in BSCs presents several challenges. One major challenge is the complexity of integrating diverse indicators across environmental, economic, and social dimensions. This complexity arises from the need to balance and prioritise multiple criteria that may conflict with each other [78]. To overcome this, employing advanced MCDM methods, such as the AHP and PROMETHEE II, provides a structured approach to handle conflicting criteria and ensures a balanced evaluation [79,80].

This paper utilized a set of 49 indicators covering both circularity and sustainability for companies in the BSC. Thus, it is not only for individual companies but also useable for the whole BSC because the indicators are concerned with all stages of the supply chain. In addition, this indicator set aligns with the United Nations SDGs and EC's guidelines on the transition to the circular economy. These indicators are also easily identified with value with the company's data.

The methodology framework integrated the LCT approach, material flow analysis with MCDM methods. The integration is based on the results of the LCT approach and MFA, which are inputs for the MCDM method. With the LCT approach, LCA, SLCA and LCC were selected to evaluate sustainability, while material flow analysis was employed to examine circularity. This approach comprehensively provides for companies and decision-makers in the assessment of sustainability and circularity. Meanwhile, due to the MCDM methods, PROMETHEE II and Entropy were chosen for ranking alternatives and weighting indicators. These techniques directly use results of the LCT approach and MFA for ranking and weighting. In addition, the sustainability and circularity indicators are quantitative, so the outranking technique of PROMETHEE is explicit, comparable and straightforward for understanding/interpreting and comparing. The weighting set of PROMETHEE II is included in an external block, which reduces the time for the decision-support processes. Moreover, it allows users to import weighting sets into that external block as their preference.

The case study on the rice straw supply chain in Pavia, Italy, examines five alternatives for generating electricity and heat, comparing a conventional approach (A0) with four circular bioeconomic alternatives (A1-A4). Environmentally, the study reveals that the most complex model (A2), which involves CO_2 capture and microalgae cultivation, significantly increases environmental impacts, particularly in global warming potential and particulate matter formation. However, A2 is good for social and economic sustainability, by creating jobs and enhancing circularity by repurposing waste materials.

Alternatives A3 and A4 offer a more balanced approach, achieving moderate environmental impacts while improving circularity through biochar and hydrochar production. These models suggest that simpler interventions can maintain sustainability without the negative trade-offs associated with more complex systems like A2. Sensitivity analysis indicates that the ranking of alternatives can shift depending on the weighting of sustainability criteria, underscoring the importance of context-specific decision-making.

While this study provides a comprehensive framework for assessing sustainability and circularity in BSCs, several limitations must be acknowledged. Firstly, the proposed decision support tool relies on available data and indicators, which may not fully capture emerging sustainability metrics or the latest advancements in technology. This limitation suggests that future research should focus on incorporating more dynamic and updated data sources, as well as exploring new sustainability indicators that reflect recent developments in the field.

Additionally, the integration of advanced technologies such as blockchain and IoT presents challenges related to scalability and practical implementation. The current study provides a theoretical framework and case study in rice straw supply chain; thus, empirical validation through diverse case studies and pilot projects is necessary to evaluate the practical effectiveness and scalability of these technologies within different supply chain contexts. Future research should conduct such empirical studies to validate and refine the proposed methods and technologies.

Another limitation is the focus on specific biomass supply chains, such as rice straw. While this provides valuable insights, it may not fully represent the diversity of BSCs. Further research should explore a broader range of biomass sources and supply chain scenarios to enhance the generalisability of the tool. Comparative studies involving different biomass types and geographical regions could offer more comprehensive insights into the applicability and limitations of the framework across various contexts [28].

Finally, the study's reliance on established MCDM methods may not address all potential uncertainties or dynamic factors affecting supply chain sustainability. Future research could investigate the integration of more advanced or hybrid decision-making approaches, including machine learning and artificial intelligence techniques, to better handle uncertainties and improve decision-making processes.

5. Conclusion

This paper highlights the need of adopting a holistic approach, taking into account both sustainability and circularity aspects, and developing a decision-supporting tool for the BSC. A case study is conducted on the application of the tool to assess different CBMs of rice straw supply chains. The obtained results indicated that not all the CBMs are better in terms of supporting sustainable development and circular economy, compared to the baseline situation. Their sustainability and circularity are largely dependent on the specific applicable technologies (outranking results of five alternatives), as well as the preference of the decision makers (outranking changes according to the objective or partially subjective weighting sets).

The results on eco-profiles of five alternatives indicate that the use of CO_2 from AD for microalgae cultivation (A2 alternative) is worse in terms of environmental sustainability, but better in social and economic sustainability and circularity, compared to the remaining alternatives. The baseline model (A0), CO_2 capture and liquefication (A1), biochar production from digestate (A3) and hydrochar production from digestate (A4) alternatives are better in terms of environmental sustainability such as environmental quality and resource depletion. However, they are worse in terms of social and economic sustainability and circularity, especially in the cases of A0 and A1 alternatives.

The outranking and sensitivity analysis results point out that the A3 alternative, which mechanically pre-treats the biomass feedstock and utilizes digestate from the AD plant for biochar production, is the most sustainable option and have the highest circularity index. It reduces negative environmental impacts, while increases the social and economic benefits compared to the baseline model (A0). Even in cases of different weighting sets are used, the A3 alternative is the best one, when considering the holistic assessment of environmental, economic, social, and circularity aspects.

The use of different weighting sets slightly changes the outranking order, and the magnitude of the outranks. In case the weight set is objectively obtained from the Entropy, the outranking order is A3>A4>A0>A1>A2. Meanwhile, with the equal and circularity-oriented weighting sets, the outranking order changes into A3>A4>A1>A0>A2. The magnitude of the outranks narrows from −0.88 to −0.23 for the worst alternative, and from 0.22 to 0.35 for the best alternative.

The study acknowledges certain limitations, including the reliance on specific case study data from the rice straw supply chain, which may not fully capture the complexities of other BSCs. Additionally, the decision support tool, while comprehensive, may require further refinement to accommodate the rapidly changing landscape of renewable energy technologies and CE practices. By addressing the identified limitations and exploring the recommended areas for future research, the study paves the way for more resilient, efficient, and sustainable biomass supply chains that align with global sustainability goals.

The application of the sustainability and circularity assessment tool in the specific rice straw supply chain indicates it contribution to the decision making process. The tool can be utilized to compare the CBM alternatives, which help the decision makers to select the most suitable alternative, considering their own preference, budget and other factors.

Nomenclature

%v/v	volume percent
AD	Anaerobic digestion
AI	Artificial intelligence
BSC	Biomass supply chain
CBM	Circular business model
CE	Circular economy
CHP	Combined heat and power
CLSC	Closed-loop supply chain
CO_2	Carbon dioxide
GWP	Global warming potential
IoT	Internet of Things
h/year	hour per year
IRR	Internal rate of return
LCA	Life cycle assessment
LCC	Life cycle costing
LCT	Life cycle thinking
m^3	cubic meter
MCDM	Multi-criteria decision-making
NG	Natural gas
NPV	Net present value
OECD	Organisation for Economic Co-operation and Development
PMF	Particulate matter formation
SLCA	Social life cycle assessment

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Data availability

Sharing of article data is not allowed due to the non-disclosure agreement between the first author and the data provider. However, the part of data which are not binded to the non-disclosure agreement will be provided on request. This tool continues to be studied for commercialization purposes, the authors agree not to publish Matlab code of the tool. However, the tool itself will be shared on request.

CRediT authorship contribution statement

Thanh Quang Nguyen: Writing – original draft, Software, Methodology, Formal analysis, Data curation. **Le Quyen Luu:** Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Nicolás Martínez-Ramón:** Writing – original draft, Visualization, Formal analysis, Data curation. **Sonia Longo:** Writing – original draft, Supervision, Methodology. **Maurizio Cellura:** Writing – original draft, Supervision, Methodology, Conceptualization. **Javier Dufour:** Writing – original draft, Supervision, Formal analysis.

Declaration of competing interest

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

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