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A multi-criteria decision-making framework and analysis of vegetable oils to produce bio-based plastics

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ABSTRACT

In the present paper, the suitability of the selected oilseeds, their corresponding vegetable oils, and few other raw materials to produce bio-based plastics was evaluated by constructing a novel criteria-based framework for Multi-Criteria Decision-Making (MCDM) analysis with a focus on the criteria of chemical functionality, sustainability, production quantity, cost, and market availability. Qualitative, semi-quantitative, and quantitative data was utilized as a base for the criteria, for which a 1–5–9 scaling technique was developed to convert the hybrid starting data into the quantitative form, when required. Additionally, two varying sets of starting data, four scenarios with differing weights of importance, as well as two different MCDM techniques, namely Technique for Order Preference and Similarity to Ideal Solution (TOPSIS) and Simple Additive Weighting (SAW), were used as a form of sensitivity analysis. The MCDM results were influenced by the dissimilar algorithm of TOPSIS and SAW techniques, resulting in different level of accuracy and a phenomenon of rank reversal, together with the developed MCDM framework in terms of the utilized data types, scaling technique, assumptions to treat data uncertainty as well as the selected criteria and scenarios. Regardless of the different starting data sets, scenarios, and MCDM techniques utilized for the MCDM analysis, tall, linseed, soybean, and palm oil were identified as the most suitable and palm kernel, coconut, and sunflower oil as the least suitable raw materials with their feature trade-offs to produce bio-based plastics. The MCDM results of the present paper can be treated as a guidepost targeted for diverse actors in the early stage of the bio-based plastics' value chain with varying point-of-views. Further, in the future, the novel MCDM framework can be of relevant significance in analysing the features of various raw materials to produce bio-based plastics.

1. Introduction

Despite their superior qualities (i.e., durability, lightness, and resource-efficiency) and often invaluable role in many applications in the current society, the traditional, fossil-based plastics can induce climate impacts and depletion of fossil resources (Spierling et al., 2020), if not manufactured, used, and disposed properly. Many of these disadvantages are due to the use of fossil crude oil as a feedstock and linear end-of-life practices of all plastics, including the bio-based ones. In this context, between 1950 and 2015, only 9 % of the globally produced plastic waste was recycled, whilst 60 % was disposed in landfills, open dumps, or, either intentionally or unintentionally, nature (Geyer et al., 2017).

Extending the use of renewable materials for plastics could help with

List of abbreviations: **MCDM**, Multi-Criteria Decision-Making; **TOPSIS**, Technique for Order Preference and Similarity to Ideal Solution; **SAW**, Simple Additive Weighting; **GHG**, Greenhouse Gas; **EDAS**, Evaluation based on Distance from Average Solution; **AHP**, Analytic Hierarchy Process; **LCA**, Life Cycle Assessment; **WF**, Water Footprint; **PIPRECIA**, Pivot Pairwise Relative Criteria Importance Assessment; **MABAC**, Multi-Attributive Border Approximation Area Comparison.

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the transition from the fossil economy to the bioeconomy (D'Amato et al., 2017), simultaneously reducing some of the environmental impacts caused by fossil-based materials, for instance the greenhouse gas (GHG) emissions and depletion of fossil resources. Nonetheless, challenges associated with renewable materials include possible problems in their availability (Wageningen Food, Biobased Research, 2017), higher costs on a weight basis in comparison to fossil-based alternatives (Kaur et al., 2017), their possible competition with food production (Ita-Nagy et al., 2020), cultivation-related direct and indirect land use (Dahiya et al., 2020; Ita-Nagy et al., 2020), eutrophication (Weiss et al., 2012), and acidification, together with GHG emissions and biodiversity loss caused by deforestation. In this discourse, multiple renewable materials have been studied as alternative building blocks for plastics, much attention being recently paid on vegetable oils (Bayan and Karak, 2017; John et al., 2019; Teo et al., 2020).

To compare different material options for diverse purposes, for example oilseeds and their corresponding vegetable oils to produce bio-based plastics, quantitatively and rationally by using several criteria, a multi-criteria decision-making (MCDM) analysis has been used (Dekamin et al., 2018; Nedeljković et al., 2021). It involves several steps: 1) identifying the objective for the MCDM analysis, 2) selecting criteria for which the alternatives are to be judged, 3) generating alternatives, 4) assigning weights to the criteria, and 5) selecting a proper MCDM technique/set of techniques to evaluate the alternatives (Seyedmohammadi et al., 2018; Thakkar, 2021). Recently, Balezentis et al. (2020) utilized MCDM techniques of Simple Additive Weighting (SAW), Technique for Order Preference and Similarity to Ideal Solution (TOPSIS), and Evaluation based on Distance from Average Solution (EDAS) to compare the cropping scenarios of rapeseed (*Brassica rapa* subsp. *oleifera*) and other oilseeds in Lithuania, whereas Dekamin et al. (2018) used Analytic hierarchy process (AHP) to identify the most suitable crops among soybean (*Glycine max* L.), rapeseed, and canola in Ardabil-Iran based on the data obtained from the integrated Life Cycle Assessment (LCA) and Water Footprint (WF) methodology.

Furthermore, Seyedmohammadi et al. (2018) applied SAW, TOPSIS, and Fuzzy TOPSIS for the cultivation priority planning of maize (*Zea mays* L. subsp. *mays*), rapeseed, and soybean in Ardabil-Iran, combined with AHP and Fuzzy AHP techniques for defining weight values of the selected criteria, whilst Nedeljković et al. (2021) used Fuzzy PIPRECIA (Pivot Pairwise Relative Criteria Importance Assessment) to form the set of criteria, integrated with Fuzzy MABAC (Multi-Attributive Border Approximation Area Comparison) to select the best rapeseed hybrid for sowing. On the other hand, a 4-year European project MAGIC (Marginal lands for Growing Industrial Crops) identified 20 most potential crops to be cultivated in European marginal lands with natural constraints by using a 1–5 scaling technique with a basis on expert opinions (Magic (Marginal lands for Growing Industrial Crops), 2018).

Noteworthy, many existing studies concentrate on locally analysing different oilseed alternatives, without taking into consideration the applications of the produced oilseeds, e.g., plastics, and consider only a few oilseed alternatives. Against this background, this paper concentrates on constructing a novel MCDM framework to investigate the suitability of several oilseed alternatives and their corresponding vegetable oils on a global scale, when possible, as renewable materials to produce bio-based plastics. This newly developed MCDM framework is further used to conduct the MCDM analysis, which utilizes TOPSIS and SAW techniques and considers multiple evaluation criteria and renewable material alternatives, as described more detailly below.

In this context, the aim of this paper is three-fold. Firstly, the goal is to construct a criteria-based framework to reveal and compare different features of the selected renewable material alternatives. Secondly, the goal is to analyse the chemical functionality, sustainability, production quantity, cost, and market availability of these materials as indicators of their suitability to produce bio-based plastics. Thirdly, the goal is to study the influence of different scenarios with varied emphasis on the suitability of the renewable material alternatives to produce bio-based plastics.

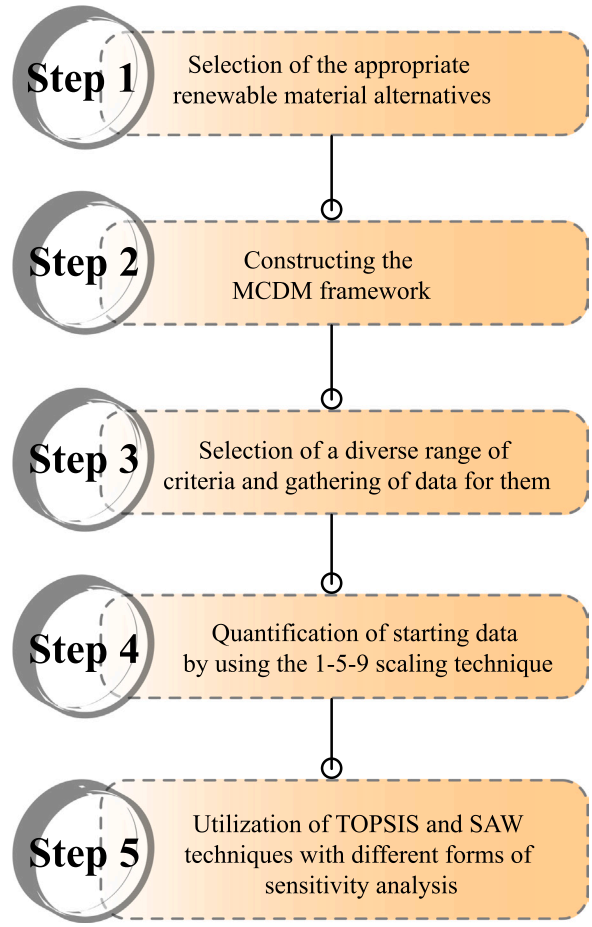

Fig. 1. A flow chart of the progress of analysis.

2. Data and methodology

2.1. Overview of the analysis

The progress of analysis conducted in this paper follows the structure of Fig. 1, the background for all the steps being described in Sections 2.2–2.9. The progress of analysis roughly includes selecting the renewable material alternatives (step 1), constructing the framework for the MCDM analysis (step 2), collecting the data for the criteria based MCDM framework (step 3), using a 1–5–9 scaling technique to quantify the collected data when required (step 4), and utilizing MCDM techniques to rank the renewable material alternatives (step 5).

2.2. Renewable material alternatives

Due to the diverse range of the selected renewable material alternatives, the umbrella term 'raw material' will be used in the present paper, referring to agricultural products (=oilseeds/fruits/beans/

kernels/nuts), by-products (=side streams caused by cultivation of oilseeds and forest-based plants or extraction of vegetable oils), vegetable oils, or plant-based oils derived from the forest-based materials. Noteworthy, in addition to oilseeds, other agricultural products and plant-based oils as well as a few by-products were included in the analysis because of their distinctive potential. Against this background, the selected raw materials consist of:

1. **Agricultural products:** oil palm fruit (*Elaeis guineensis* Jacq.), oil palm kernel (*Elaeis guineensis* Jacq.), soybean, rapeseed, sunflower seed (*Helianthus annuus* L.), linseed (*Linum usitatissimum* L.), castor bean (*Ricinus communis* L.), and coconut (*Cocos nucifera* L.) together with the seeds of jatropha (*Jatropha curcas* L.) and vernonia (*Vernonia galamensis* L.).
2. **By-products:** palm fatty acid distillate (PFAD) and black liquor (the raw material for tall oil).
3. **Vegetable oils:** palm, palm kernel, crude palm (the raw material for PFAD), soybean, rapeseed, sunflower, linseed, castor, coconut, jatropha, and vernonia oil.
4. **Plant-based oil:** tall oil.

2.3. Selected criteria and data collection

2.3.1. Categorization: stage 1, 2, and 3

To select a rigorous set of criteria to construct the MCDM framework and evaluate the features of different renewable material alternatives, the raw materials depicted in Section 2.2 were divided into three categories, namely stage 1, 2, and 3 (see Fig. 2). Stage 1 represents the first stage in the value chain of bio-based plastics: the production of agricultural products or by-products, in other words, the cultivation phase. Stage 2 consists of the oil extraction phase of vegetable or other plant-based oils, whereas stage 3 refers to the final phase, market availability of vegetable oil and other plant oil-based plastics. In the following Sections 2.4.2 - 2.4.4, all the selected criteria per stage 1, 2, and 3 are introduced and steps of data collection explained. The criteria have been selected by using literature- and expert consultation-based methods (Xiang et al., 2018), and the collected background data for these criteria can be found in the supplementary information.

2.3.2. Stage 1: agricultural product or by-product

2.3.2.1. Feedstock type. The purpose of this criterion is to express whether the raw material can be categorized as an agricultural product or a side stream. The data collection of this criterion was based on the discussions among authors (see Table 1 in supplementary information).

2.3.2.2. Oil content. For the criterion, the oil content of raw materials was collected from different literature sources (see Table 2 in supplementary information): in the case of ranging values, an average was taken. For black liquor, which does not contain oil, the content of fatty and resin acids (the precursors of tall oil (Foran, 1992)) in five different pine species were collected from Foran (1992). Pine (*genus Pinus*) as a wood species was selected because it is mostly used to produce tall oil.

2.3.2.3. Cultivation on marginal and contaminated land. This criterion examines the extent to which different raw materials could be cultivated on marginal and contaminated land for the industrial purposes, excluding food production. The data was obtained from several literature sources (see Table 3 in supplementary information).

2.3.2.4. Knowhow for cultivation. In this criterion, the performance of each agricultural product was evaluated based on the existing cultivation knowledge including climatic and agro-climatic growth conditions, cultivation management practices for optimal growth, and existence of improved varieties. The data was collected from several literature sources (see Table 4 in supplementary information).

2.3.2.5. Competition with food production. For this criterion, the focus was set on evaluating which raw materials are mostly cultivated either for the food industry or other industrial purposes. The data collection

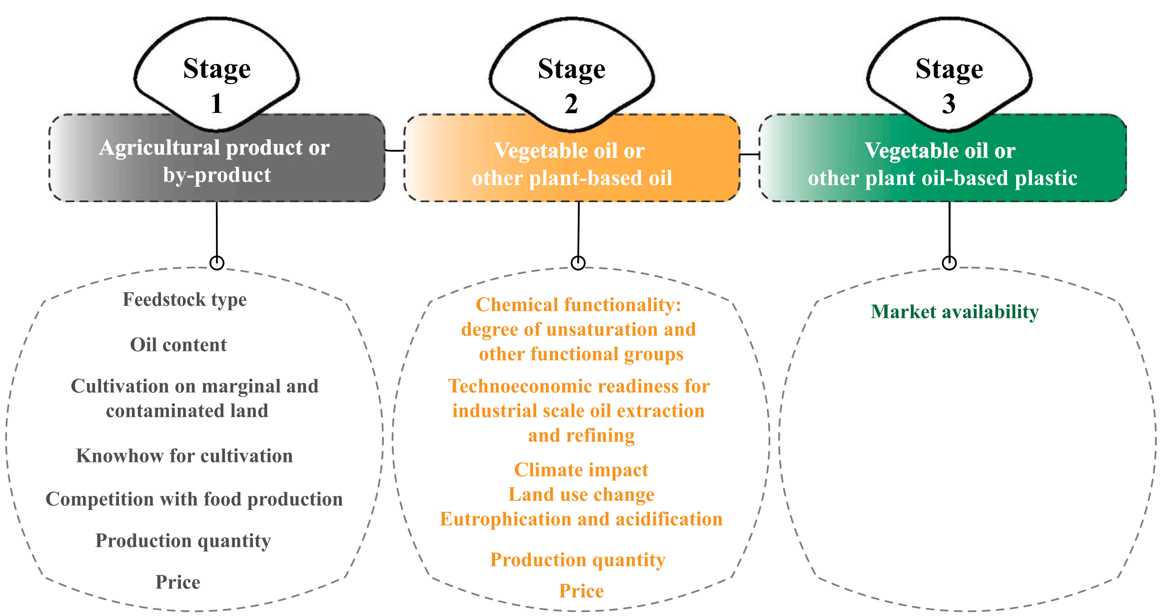

Fig. 2. A scheme revealing the categorization and criteria of potential raw materials to produce bio-based plastics.

Table 1
Selection criteria and their relative weights per scenario 1, 2, 3, and 4, respectively. The most important criteria within different scenarios are highlighted with yellow.

	Criteria	Weights of importance			
		Scenario 1 Basic	Scenario 2 Producer of plastic	Scenario 3 Environmentalist	Scenario 4 Farmer
	Stage 1				
1	Feedstock type	0.040	0.032	0.128	0.032
2	Oil content	0.080	0.032	0.026	0.161
3	Cultivation on marginal and contaminated land	0.080	0.032	0.128	0.032
4	Knowhow for cultivation	0.040	0.032	0.026	0.161
5	Competition with food production	0.080	0.032	0.128	0.032
6	Production quantity of agricultural product	0.040	0.032	0.026	0.161
7	Price of agricultural product	0.040	0.032	0.026	0.161
	Stage 2				
8	Chemical functionality: degree of unsaturation and other functional groups	0.080	0.161	0.026	0.032
9	Technoeconomic readiness for industrial scale oil extraction and refining	0.080	0.032	0.026	0.032
10	Climate impact	0.080	0.032	0.128	0.032
11	Land use change	0.080	0.032	0.128	0.032
12	Eutrophication & acidification	0.040	0.032	0.128	0.032
13	Production quantity of vegetable oil	0.080	0.161	0.026	0.032
14	Price of vegetable oil	0.080	0.161	0.026	0.032
	Stage 3				
15	Market availability	0.080	0.161	0.026	0.032

Table 2
Hybrid starting data matrix for the sector 1: agricultural product or by-product, containing both quantitative and scaled data. In the case of the criteria treated with the three-step scaling technique, the scales 1, 5, and 9 represent poor, moderate, and good performances of raw materials, respectively, whilst in terms of the criteria treated with the two-step scaling technique, 1 represents 'no' and 5 'yes'.

	Agricultural product or by-product						
	Feedstock type	Oil content (%)	Cultivation on marginal and contaminated land	Knowhow for cultivation	Competition with food production	Production quantity (Mt)	Price (US $/t)
Oil palm fruit	1	50,0	5	9	1	319,9	133,1
Oil palm kernel	1	2,0	5	9	1	308,4	464,1
Crude palm oil	5	17,5	5	9	5	62,0	747,3
Soybean	1	20,0	5	9	1	306,3	395,1
Rapeseed	1	44,5	9	9	1	70,4	541,2
Sunflower seed	1	38,5	5	9	1	44,6	484,4
Linseed	1	38,0	9	9	5	2,5	463,4
Black liquor	5	37,2	9	9	5	102,6	0,0
Castor bean	1	40,0	9	5	5	1,9	494,6
Coconut	1	62,5	5	9	1	59,9	180,8

Table 3
Hybrid starting data matrix for the sector 2: vegetable or other plant-based oil, containing both quantitative and scaled data. In the case of the criteria treated with the three-step scaling technique, the scales 1, 5, and 9 represent poor, moderate, and good performances of raw materials, respectively, whilst in terms of the criteria treated with the two-step scaling technique, 1 represents 'no' and 5 'yes'. The abbreviations SNA and SSA, in turn, stand for the environmental impacts of soybean cultivated in North America (USA or Canada) or South America (Argentina or Brazil), respectively.

	Vegetable or other plant-based oil						
	Chemical functionality: degree of unsaturation and other functional groups	Technoeconomic readiness for industrial scale oil extraction and refining	Environmental impacts: climate impact	Environmental impacts: land use change	Environmental impacts: eutrophication and acidification	Production quantity (Mt)	Price (US$/t)
Palm oil	1	9	5	9	5	59,1	761,2
Palm kernel oil	1	5	1	5	9	6,6	1115,9
PFAD	1	5	9	9	9	0,7	584,6
Soybean oil	5	9	9 (SNA) or 1 (SSA)	9 (SNA) or 1 (SSA)	5	48,6	892,7
Rapeseed oil	5	9	9	9	9	24,6	973,4
Sunflower oil	5	9	5	9	5	15,8	926,5
Linseed oil	9	5	9	9	9	0,7	1067,1
Tall oil	5	9	9	9	9	1,7	712,4
Castor oil	5	5	1	9	1	0,01	1651,7
Coconut oil	1	5	5	9	5	3,1	1256,2

Table 4
Hybrid starting data matrix for the sector 3: vegetable or other plant oil-based plastic. The represented values are based on the method of content analysis (see Section 2.3.4).

	Vegetable or other plant oil-based plastic
	Market availability
Palm oil	1
Palm kernel oil	3
PFAD	0
Soybean oil	9
Rapeseed oil	3
Sunflower oil	1
Linseed oil	6
Tall oil	4
Castor oil	23
Coconut oil	0

was based on the literature screening as well as discussions among authors (see Table 1 in supplementary information).

2.3.2.6. Production quantity. Data for the production quantity in tonnes (t) of raw materials over the period of 2011–2018 was collected from FAOSTAT database (FAOSTAT, 1997), excluding crude palm oil, black liquor as well as jatropha and vernonia seed due to the lack of available data (see Table 8 in supplementary information). In the case of oil palm kernel, the data was available only for the years of 2014–2018, and the value for crude palm oil was estimated by using the knowledge from Zero, Rainforest Foundation Norway (2016) stating that 95 % of crude palm oil is refined into palm oil. Additionally, the value for black liquor was estimated by using the papers of Aryan and Kraft (2021) and Kim et al. (2019) stating that the global production quantity (as dry solids) of black liquor is about 1.5 tonnes per tonne of the produced softwood kraft pulp. For further evaluation, the raw data was converted into mega tonnes (Mt) and an average of all the values per raw material over the applicable period was taken.

2.3.2.7. Price. The data about the price of raw materials, excluding oil palm kernel, crude palm oil, black liquor as well as jatropha and

Table 5
The results of TOPSIS for raw materials using scenarios 1, 2, 3, and 4 with different relative weights and data for soybean considering the location of its cultivation. The abbreviations of SNA and SSA stand for soybean cultivated in North America (USA or Canada) or South America (Brazil or Argentina), respectively. For simplicity in reporting the results, the umbrella term of vegetable or plant-based oil is used, this term containing both the specific agricultural product or by-product and its respective vegetable or plant-based oil. Noteworthy, in scenario 4 (farmer), PFAD and tall oil were excluded from the analysis due to their non-cultivated nature as by-products.

Raw materials	Scenario 1 (Basic)		Scenario 2 (Producer of plastic)		Scenario 3 (Environmentalist)		Scenario 4 (Farmer)	
	SNA	SSA	SNA	SSA	SNA	SSA	SNA	SSA
Palm oil	0.402	0.470	0.425	0.437	0.278	0.325	0.644	0.755
Palm kernel oil	0.223	0.234	0.180	0.181	0.314	0.326	0.474	0.474
PFAD	0.346	0.366	0.225	0.228	0.706	0.720	n.d.	n.d.
Soybean oil	0.517	0.459	0.550	0.546	0.399	0.235	0.580	0.568
Rapeseed oil	0.418	0.436	0.344	0.346	0.455	0.488	0.420	0.424
Sunflower oil	0.329	0.351	0.284	0.286	0.292	0.356	0.367	0.370
Linseed oil	0.459	0.473	0.394	0.395	0.547	0.570	0.373	0.378
Tall oil	0.455	0.469	0.314	0.315	0.794	0.804	n.d.	n.d.
Castor oil	0.506	0.510	0.519	0.520	0.393	0.419	0.353	0.355
Coconut oil	0.303	0.323	0.131	0.136	0.294	0.356	0.535	0.537

Table 6
The ranking of raw materials with TOPSIS using scenarios 1, 2, 3, and 4 with different relative weights and data for soybean considering the location of its cultivation. The abbreviations of SNA and SSA stand for soybean cultivated in North America (USA or Canada) or South America (Brazil or Argentina), respectively. For simplicity in reporting the results, the umbrella term of vegetable or plant-based oil is used, this term containing both the specific agricultural product or by-product and its respective vegetable or plant-based oil. Noteworthy, in scenario 4 (farmer), PFAD and tall oil were excluded from the analysis due to their non-cultivated nature as by-products.

Raw materials	Scenario 1 (Basic)		Scenario 2 (Producer of plastic)		Scenario 3 (Environmentalist)		Scenario 4 (Farmer)	
	SNA	SSA	SNA	SSA	SNA	SSA	SNA	SSA
Palm oil	6	3	3	3	10[b]	9[b]	1[a]	1[a]
Palm kernel oil	10[b]	10[b]	9	9	7	8	4	4
PFAD	7	7	8	8	2	2	n.d.	n.d.
Soybean oil	1	5	1[a]	1[a]	5	10	2	2
Rapeseed oil	5	6	5	5	4	4	5	5
Sunflower oil	8	8	7	7	9	6	7	7
Linseed oil	3	2	4	4	3	3	6	6
Tall oil	4	4	6	6	1[a]	1[a]	n.d.	n.d.
Castor oil	2[a]	1[a]	2	2	6	5	8[b]	8[b]
Coconut oil	9	9	10[b]	10[b]	8	7	3	3

[a]The most suitable raw material within a specific scenario.
[b]The least suitable raw material within a specific scenario.

Table 7
The results of SAW for raw materials using scenarios 1, 2, 3, and 4 with different relative weights and data for soybean considering the location of its cultivation. The abbreviations of SNA and SSA stand for soybean cultivated in North America (USA or Canada) or South America (Brazil or Argentina), respectively. For simplicity in reporting the results, the umbrella term of vegetable or plant-based oil is used, this term containing both the specific agricultural product or by-product and its respective vegetable or plant-based oil. Noteworthy, in scenario 4 (farmer), PFAD and tall oil were excluded from the analysis due to their non-cultivated nature as by-products.

Raw materials	Scenario 1 (Basic)		Scenario 2 (Producer of plastic)		Scenario 3 (Environmentalist)		Scenario 4 (Farmer)	
	SNA	SSA	SNA	SSA	SNA	SSA	SNA	SSA
Palm oil	0.593	0.593	0.529	0.529	0.541	0.541	0.642	0.642
Palm kernel oil	0.358	0.358	0.307	0.307	0.425	0.425	0.451	0.451
PFAD	0.569	0.569	0.424	0.424	0.793	0.793	n.d.	n.d.
Soybean oil	0.628	0.486	0.607	0.551	0.598	0.370	0.589	0.532
Rapeseed oil	0.626	0.626	0.509	0.509	0.684	0.684	0.538	0.538
Sunflower oil	0.510	0.510	0.427	0.427	0.503	0.503	0.461	0.461
Linseed oil	0.647	0.647	0.529	0.529	0.769	0.769	0.503	0.503
Tall oil	0.707	0.707	0.539	0.539	0.885	0.885	n.d.	n.d.
Castor oil	0.532	0.532	0.473	0.473	0.533	0.533	0.382	0.382
Coconut oil	0.437	0.437	0.287	0.287	0.480	0.480	0.488	0.488

Table 8
The ranking of raw materials with SAW using scenarios 1, 2, 3, and 4 with different relative weights and data for soybean considering the location of its cultivation. The abbreviations of SNA and SSA stand for soybean cultivated in North America (USA or Canada) or South America (Brazil or Argentina), respectively. For simplicity in reporting the results, the umbrella term of vegetable or plant-based oil is used, this term containing both the specific agricultural product or by-product and its respective vegetable or plant-based oil. Noteworthy, in scenario 4 (farmer), PFAD and tall oil were excluded from the analysis due to their non-cultivated nature as by-products.

Raw materials	Scenario 1 (Basic)		Scenario 2 (Producer of plastic)		Scenario 3 (Environmentalist)		Scenario 4 (Farmer)	
	SNA	SSA	SNA	SSA	SNA	SSA	SNA	SSA
Palm oil	5	4	3	3	6	5	1[a]	1[a]
Palm kernel oil	10[b]	10[b]	9	9	10[b]	9[b]	7	7
PFAD	6	5	8	8	2	2	n.d.	n.d.
Soybean oil	3	8	1[a]	1[a]	5	10	2	3
Rapeseed oil	4	3	5	5	4	4	3	2
Sunflower oil	8	7	7	7	8	7	6	6
Linseed oil	2	2	4	4	3	3	4	4
Tall oil	1[a]	1[a]	2	2	1[a]	1[a]	n.d.	n.d.
Castor oil	7	6	6	6	7	6	8[b]	8[b]
Coconut oil	9	9	10[b]	10[b]	9	8	5	5

[a]The most suitable raw material within a specific scenario.
[b]The least suitable raw material within a specific scenario.

vernonia seed due to the lack of data, was obtained from FAOSTAT with a basis on two different datasets: gross production value (current thousand US$) and production quantity (t) (see Table 8 in supplementary information) (FAOSTAT, 1997). The data was obtained for the years of 2011–2018. The final raw material price was calculated by combining the two previously mentioned datasets into US$/t and taking an average over the applicable period. As an exception, the value of palm kernel was estimated by using the data obtained from Ehirim (2004) over the period of 1999–2003, the average value of crude palm oil was calculated from the data of OIL WORLD in US$/t over the period of 2011–2018 with a basis on the palm oil's biggest production country Indonesia (OIL WORLD. ISTA Mielke GmbH, 1958), and black liquor was assumed to be a process intermediate, therefore having no value for the price.

2.3.3. Stage 2: vegetable or other plant-based oil

2.3.3.1. Chemical functionality: degree of unsaturation and other functional groups. This criterion indicates the number (the sum) of functional groups within the different fatty acids in the vegetable or other pant-based oil, whether they are carbon-carbon double bonds, hydroxyl groups, or epoxy groups, which influence (but not solely) on the readiness of modification for further applications, in the case of the present paper, many types of plastics. In this criterion, the data collection was based on literature screening (see Table 5 in supplementary information) from which the type and number of functional groups within the fatty acids per vegetable or other plant-based oil as well as the proportion of different fatty acids in these oils were able to be obtained.

2.3.3.2. Technoeconomic readiness for industrial scale oil extraction and refining. For the criterion, data about the level of extraction and refining processes of raw materials was collected from the book chapters, scientific papers, and websites with the focus on their technical and economic feasibility (see Table 6 in supplementary information).

2.3.3.3. Environmental impacts. Environmental impacts of cultivation, refining, and extraction of raw materials in terms of GHG emissions (=climate impact) (kg CO_2 eq./kg refined oil), land use change (kg CO_2 eq./kg refined oil), eutrophication impact (kg PO_4 eq./kg refined oil), and acidification impact (kg H^+ eq./kg refined oil) were obtained from the databases of Ecoinvent and Agri-footprint, excluding jatropha seed/ jatropha oil and vernonia seed/vernonia oil due to the lack of data. The data was collected from several countries in which the raw material is cultivated.

2.3.3.4. Production quantity. Global production quantities of the refined vegetable or other plant-based oils in tonnes over the period of 2011–2018, excluding jatropha and vernonia oil, were obtained from the FAOSTAT database (see Table 8 in supplementary information) (FAOSTAT, 1997). As an exception, the obtained period for castor oil was 2014–2018 and the production quantity of PFAD (only over the period of 2012–2018 due to the lack of available data) and crude tall oil was estimated based on the data obtained from Mantari et al. (2020) and Aryan and Kraft (2021), respectively. For further evaluation, the raw data was converted into mega tonnes and the average value was taken per vegetable or other plant-based oil over the applicable period.

2.3.3.5. Price. The price of different vegetable or other plant-based oils as monthly price averages (US$/t), excluding tall oil as well as jatropha and vernonia seed due to the lack of available data, was obtained from OIL WORLD over the time of 2011–2018 (OIL WORLD. ISTA Mielke GmbH, 1958). The period of seven years in comparison to five years or the most recent year was selected for the analysis, because it was thought to indicate the cumulative increase in price better over the other alternatives. The geographical location for the whole data was selected to be the individual vegetable or other plant-based oil's biggest production country, whereas for soybean and sunflower oil, an average value across the different cultivation countries was calculated. Further, the average vegetable or other plant-based oil price (US$/t), representing the cumulative price increase per each oil over the given period, was calculated. The only exception was PFAD for which the data was available only for the years of 2013–2018. Additionally, the data assumption for tall oil over the years of 2011–2013 was obtained from Peters and Stojcheva (2017) and turned into US$/t by using the average exchange rates in 2011, 2012, and 2013, respectively.

2.3.4. Stage 3: vegetable oil or other plant oil-based plastic

2.3.4.1. Market availability. The indicative availability of existing vegetable and other plant oil-based plastics on the markets in 2020–2021 was screened by searching various published scientific papers, reports, as well as existing company websites (see Table 7 in supplementary information). The selected methodology for data collection was content analysis, which can be used to quantify text-based qualitative data (Krippendorff, 2018) (see Table 8 in supplementary information for the details).

2.4. Missing data

In general, the challenge of missing data was solved by making assumptions based on data obtained from the scientific papers, as depicted in Sections 2.4.2 - 2.4.4. Despite this, among the raw materials under analysis, vernonia and jatropha seed, together with their corresponding oils, had the highest number of missing data (47 % and 40 %, respectively) per all 15 criteria.

2.5. 1–5–9 scaling technique

Hybrid starting data was compiled for MCDM analysis, consisting of both qualitative, semi-quantitative, and quantitative data. Nonetheless, only quantitative data is suitable for MCDM techniques of TOPSIS and SAW. Therefore, 1–5–9 scaling technique was used to turn the qualitative or semi-quantitative data into the quantitative one as well as to report quantitative data with a basis on a paid source. In this scaling technique, the performance of each raw material per criterion was ranked from 1 to 9 (three-step scale), 1 representing poor, 5 satisfactory, and 9 good performances, or by using the scaling from 1 to 5 (two-step scale), depending on the type of criteria (see Table 8-14 in supplementary information for the details).

2.6. Scenarios and their relative criteria weights

Four scenarios were developed based on different point-of-views of various stakeholders operating in the plastics' value chain, namely, scenario 1 (basic), scenario 2 (producer of plastic), scenario 3 (environmentalist), and scenario 4 (farmer). The total sum of relative weights per each scenario was selected to be 1 (Thakkar, 2021), consisting of a scenario-dependent set of the most important and less important criteria constructed by the authors. Subjective weighting method of direct rating was further used to attribute these weights with a basis on expert preferences (Bottomley and Doyle, 2001; Xiang et al., 2018). In scenario 1, the most important criteria were assigned to have two times higher weight in comparison to the less important criteria, whereas in scenarios 2, 3, and 4 this difference in the magnitude of weights was assigned to be quintuple. All the relative criteria weights in the respective scenarios are defined in Table 1.

2.7. MCDM analysis – the TOPSIS technique

In this paper, TOPSIS technique was utilized for the MCDM analysis. TOPSIS is the most used, simple, and efficient MCDM technique

(Lakshmi, 2016; Thakkar, 2021), first developed by Hwang and Yoon (1981) (Seyedmohammadi et al., 2018). According to Balezentis et al. (2020), the principle of TOPSIS is to choose the option with the shortest distance from the positive-ideal and with the longest distance from the negative-ideal solutions.

Firstly, the values of different criteria are converted into unitless and therefore comparable values by using the vector normalization according to the Eq. (4). Vector normalization was selected because it has been classically utilized in TOPSIS. (Lakshmi et al., 2016).

$$r_{ij} = x_{ij} \Big/ \sqrt{\sum_{1}^{n} x_{ij}^2} \tag{4}$$

where r_{ij} stands for the normalized value of an alternative (j) within a criterion (i) and x_{ij} for the starting value of an alternative (j) within a criterion (i).

Secondly, the weights of importance were decided to the different criteria with Eq. (5).

$$\omega_{ij} = 1, 2 \ldots n \tag{5}$$

where ω_{ij} stands for the weight of importance of an alternative (j) within a criterion (i) and n for the value of the weight of importance of an alternative (j) within a criterion (i).

Thirdly, the weighted normalized matrix was calculated according to the Eq. (6).

$$v_{ij} = \omega_{ij} \times r_{ij} \tag{6}$$

where v_{ij} stands for the weighted value, ω_{ij} for the value of the weight of importance, and r_{ij} for the normalized value of an alternative (j) within a criterion (i), respectively.

Next, the positive-ideal as well as negative-ideal solutions were determined by using the Eqs. (7) and (8). In the present paper, the price of agricultural product or by-product and vegetable or other plant-based oil belonged to the cost criteria, whereas the rest of the criteria fell to the category of benefit criteria.

$$A^* = \left\{ \left(maxv_{ij} \middle| , j \in J \right) \ , \ \left(minv_{ij} \middle| , j \ \in J' \right) \right\} \tag{7}$$

$$A^- = \left\{ \left(minv_{ij} \middle| , j \in J \right) \ , \ \left(maxv_{ij} \middle| , j \ \in J' \right) \right\} \tag{8}$$

where A^* stands for the positive-ideal and A^- for the negative-ideal solution, $maxv_{ij}$ for the maximum value of an alternative (j) within either a benefit (J) or cost (J') criterion (i), and $minv_{ij}$ for the minimum value of an alternative (j) within either a benefit (J) or cost (J') criterion (i).

These steps were followed by calculating the separation of each alternative from the positive-ideal and negative-ideal solution according to the Eqs. (9) and (10).

$$S_i^* = \sqrt{\sum_{1}^{n} \left(v_{ij} - v_j^* \right)^2 j = 1 \quad where \quad i = 1, 2 \ldots, \quad m} \tag{9}$$

$$S_i^- = \sqrt{\sum_{1}^{n} \left(v_{ij} - v_j^- \right)^2 j = 1 \quad where \quad i = 1, 2 \ldots, \quad m} \tag{10}$$

where S_i^* stands for the separation of an alternative (j) from the positive-ideal solution, S_i^- for the separation of an alternative (j) from the negative-ideal solution, v_{ij} for the weighted value of an alternative (j) within a criterion (i), v_j^* for the positive-ideal solution within a criterion (i), and v_j^- for the negative-ideal solution within a criterion (i).

Lastly, the relative closeness of the alternatives to the ideal solution was calculated with Eq. (11). After this, to find out the most suitable alternatives, the alternatives under study were arranged with the decreasing order of the C_i^*values. The highest (maximum of 1) and lowest (minimum of 0) value indicated the best and worst performance, respectively, among different alternatives.

$$C_i^* = S_i^- \big/ \left(S_i^* + S_i^- \right), 0 \leq C_i^* \leq 1 \ \ where \ \ i = 1, 2, \ldots, m \tag{11}$$

where C_i^* stands for the relative closeness of an alternative (j) to the ideal solution, S_i^- for the separation of an alternative (j) from the negative-ideal solution, and S_i^* for the separation of an alternative (j) from the positive-ideal solution.

2.8. MCDM analysis – the SAW technique

In addition to TOPSIS, SAW technique was selected for the MCDM analysis. SAW technique has been reported to be a very simple and preferred technique for less complex problems (Thakkar, 2021). Its main idea is to multiply the normalized values of a specific alternative with the relative weight of the selected criteria: the result is the sum of all these weighted values per alternative, which, in the end, are ranked in the decreasing order (Thakkar, 2021). The technique consists of the following equations as presented according to Balezentis et al. (2020):

$$S_j = \sum_{i=1}^{m} \omega_i \bar{r}_{ij} \tag{12}$$

where ω_i stands for the weight of importance of a specific criterion (i) and $\bar{r}_{ij}$ for the normalized value of either cost (Eq. 13) or benefit criteria (Eq. 14), into either of which the utilized criteria are divided. As in the case of TOPSIS, the price of agricultural product or by-product and vegetable or other plant-based oil belonged to the cost criteria, whereas the rest of the criteria fell to the category of benefit criteria.

$$\bar{r}_{ij} = min_j r_{ij} / r_{ij} \tag{13}$$

$$\bar{r}_{ij} = r_{ij} / max_j r_{ij} \tag{14}$$

where $\bar{r}_{ij}$ stands for the normalized value of either cost or benefit criterion, r_{ij} for the starting value of an alternative (j) within a criterion (i), $min_j r_{ij}$ for the minimum value of an alternative (j) within a criterion (i), and $max_j r_{ij}$ for the maximum value of an alternative (j) within a criterion (i).

2.9. Sensitivity analysis

The sensitivity analysis performed in the present paper was based on three approaches: the use of two techniques for MCDM analysis (as depicted in Sections 2.7 and 2.8), four differing scenarios with their respective weights (as depicted in Section 2.6), and two alternating values as starting data per each scenario. More specifically, these three values of starting data are related to the environmental impacts (climate impact, land use change as well as eutrophication and acidification impact) of soybean and soybean oil, for which the values of environmental impacts significantly differ depending on the location in which the cultivation and oil extraction occurs, in North America (USA or Canada) or South America (Brazil or Argentina).

3. Results

3.1. Hybrid starting data matrixes

The finalized tables containing the hybrid starting data for MCDM techniques of TOPSIS and SAW can be found in Tables 2, 3, and 4 for the sectors 1, 2, and 3, respectively. Noteworthy, due to the lack of data (see Section 2.4 and supplementary information) and despite their potential, the raw materials of jatropha and vernonia seed together with their corresponding vegetable oils were excluded from the MCDM analysis to prevent the distortion of the MCDM results.

3.2. TOPSIS technique and sensitivity analysis

As Balezentis et al. (2020) implies the role of MCDM analysis is to model the trade-offs among multiple criteria and based on this, identify the most promising alternative. Therefore, it is reasonable that MCDM as a technique does not provide one “right” solution, more likely the results are ambiguous and dependent on the applied MCDM techniques, scenarios (point-of-views) with their weights of importance, as well as data utilized for the analysis. Consequently, the analysis conducted in the present Section 3.2 (with a focus on TOPSIS) and the following Section 3.3 (with a focus on SAW) considers two aspects to interpret the obtained TOPSIS and SAW results, namely scenario-specific analysis, in other words, the performance of the raw materials within and across scenarios with a specific point-of-view, and data-specific analysis, in more detail, the effect of the use of varying starting data on the performance of raw materials within and across scenarios. The results of MCDM analysis have been compiled in Tables 5 and 6 for TOPSIS and Tables 7 and 8 for SAW, respectively.

In terms of the first aspect, namely scenario-specific analysis, the scenarios 1 (basic) and 2 (producer of plastic) share similar results considering the most and least suitable raw materials to produce bio-based plastics. In more detail, castor oil performs well, having the ranking of 1 (SSA) and 2 (SNA) in scenario 1 and ranking of 2 (SNA and SSA) in scenario 2, together with soybean oil with the order of ranking of 1 and 5 (SNA and SSA) in scenario 1 and 1 (SNA and SSA) in scenario 2. Simultaneously, coconut and palm kernel oil perform the worst in the case of both data sets of SNA and SSA and scenarios 1 and 2, having the order of ranking of 10 and 9 (data sets of SNA and SSA) as well as 9 and 10 (data sets of SNA and SSA), respectively. In the scenario 3 (environmentalist), in turn, the by-products of tall oil and PFAD perform excellently (having the ranking of 1 and 2, respectively, in both data sets of SNA and SSA) in the case of all the weighted criteria, excluding the moderate performance of PFAD for the criterion of cultivation on marginal and contaminated land, while palm oil obtains the worst order of ranking of 10 and 9 for the data sets of SNA and SSA, respectively. In the end, in the scenario 4 (farmer), palm and soybean oil perform excellently (having the ranking of 1 and 2, respectively, in both data sets of SNA and SSA) across all the weighted criteria, excluding the rather low oil content of soybean oil, whilst castor and sunflower oil perform mainly poorly or moderately in the case of the weighted criteria, therefore obtaining the worst order of ranking of 7 and 8, respectively, in both data sets of SNA and SSA. Noteworthy, in general, the order of ranking of palm oil significantly changes across all the scenarios and both data sets.

In terms of the second aspect, namely data-specific analysis, the final C_i^* values of TOPSIS results range between 0.223 and 0.794. Additionally, the order of ranking of soybean oil is reasonably lower in the SSA data set due to its significantly higher associated environmental impacts in comparison to the data set of SNA in the scenarios 1 and 3, whereas in the scenarios 2 and 4, the order of ranking of soybean oil and other raw materials remain the same with only subtle changes in the final MCDM values of the individual raw materials. Further, the data set SSA contains more changes in the order of ranking of all the raw materials in comparison to the data set of SNA. Simultaneously, mainly subtle changes (and mostly improvement) in the order of ranking occurs in the case of palm, rapeseed, linseed, and castor oil (scenario 1) as well as palm, palm kernel, sunflower, castor, and coconut oil (scenario 3). This latter finding indicates that the attributes and part of the steps in TOPSIS are connected to each other. Especially in the normalization step, a small change even in one starting data of an alternative can impact in many existing values within a criterion. This in turn, effects on the weighted values, which have an impact on the values of positive and ideal separation, etc. More detailed discussion of this phenomenon can be found in Section 4.1.

3.3. SAW technique and sensitivity analysis

Based on the scenario-specific analysis, varying scenarios contain very similar order of ranking in terms of the most and least suitable raw materials, regardless of the utilized data set. Namely, in the case of both data sets of SNA and SSA, tall oil performs the best, followed by linseed oil (basic scenario 1), whereas in scenario 2 (producer of plastic), soybean oil possesses the most suitable performance, followed by tall oil. In scenario 3 (environmentalist), in turn, tall oil performs the best, followed by PFAD, while in scenario 4 (farmer), palm oil obtains the most suitable performance, followed by soybean oil (in both data sets of SNA and SSA). In the similar manner, in scenarios 1, 2, and 3, palm kernel and coconut oil obtain the worst performances, whereas in the scenario 4, castor oil, followed by palm kernel oil, perform the worst among raw materials.

In terms of the data-specific analysis, in turn, the final values of SAW results range between 0.287 and 0.793. It can also be stated that, as in TOPSIS, the significantly higher environmental impacts of soybean oil in the data set of SSA in comparison to SNA worsen the order of ranking of soybean oil in all the scenarios, except of scenario 2, the producer of plastic. This is since scenario 2 does not considerably weight the environmental impacts of raw materials over other criteria. The biggest change in the order of ranking of soybean oil can be seen in scenarios 1 and 3, in which the change in the order of ranking is in the order of magnitude of five. Additionally, as opposed to TOPSIS, the change in the starting value in SAW only alters the final value of that raw material (in the present paper, the final value of soybean oil), while the final values of other raw materials remain the same between the data sets of SNA and SSA. Despite this, simultaneously, the general order of ranking of raw materials slightly changes in the form of a subtle improvement of magnitude of one or two. Further, as in TOPSIS, the order of ranking of all the raw materials alters more powerfully in the case of the data set SSA than SNA, which is due to the considerably increased movement of soybean oil in its order of ranking. More detailed discussion considering the results of SAW can be found from the Section 4.1.

4. Discussion

4.1. MCDM techniques and order of ranking

As can be seen from Section 3, techniques of TOPSIS and SAW are able to provide a coherent and rather similar representation of the studied phenomenon, but they evidently yield slightly differing order of ranking of the raw materials. This has been reported to be due to the differing algorithm, namely equations, of these techniques, particularly normalization and weighting approaches (Sunarti et al., 2018; Widianta et al., 2018). Additionally, in some studies, TOPSIS has shown better accuracy of results in comparison to SAW (Firgiawan et al., 2020; Widianta et al., 2018). The higher level of accuracy of TOPSIS due to the differing algorithm, also resulting in higher sensitivity, may also explain the raw materials' more powerful change in their order of ranking between the specific scenarios and data sets of SNA and SSA, when compared to the results of SAW. TOPSIS also yields slightly higher range of the final MCDM values within individual scenarios in comparison to SAW.

More specifically, the utilization of datasets of SNA and SSA in MCDM analysis of the present paper also moderately changes the final MCDM values of all the raw materials per scenario in the case of TOPSIS, whereas in terms of SAW, the change in these final values occurs only for the raw material for which the starting data has been changed. This phenomenon called rank reversal is traditionally attributed to TOPSIS and is reported to be particularly caused by the normalization step as well as, in general, the non-independence of the criteria (Socorro García-Cascales and Lamata, 2012). One proposed approach to solve the rank reversal consists of the modification of the normalization equation together with the values of positive and negative ideal solution (Socorro

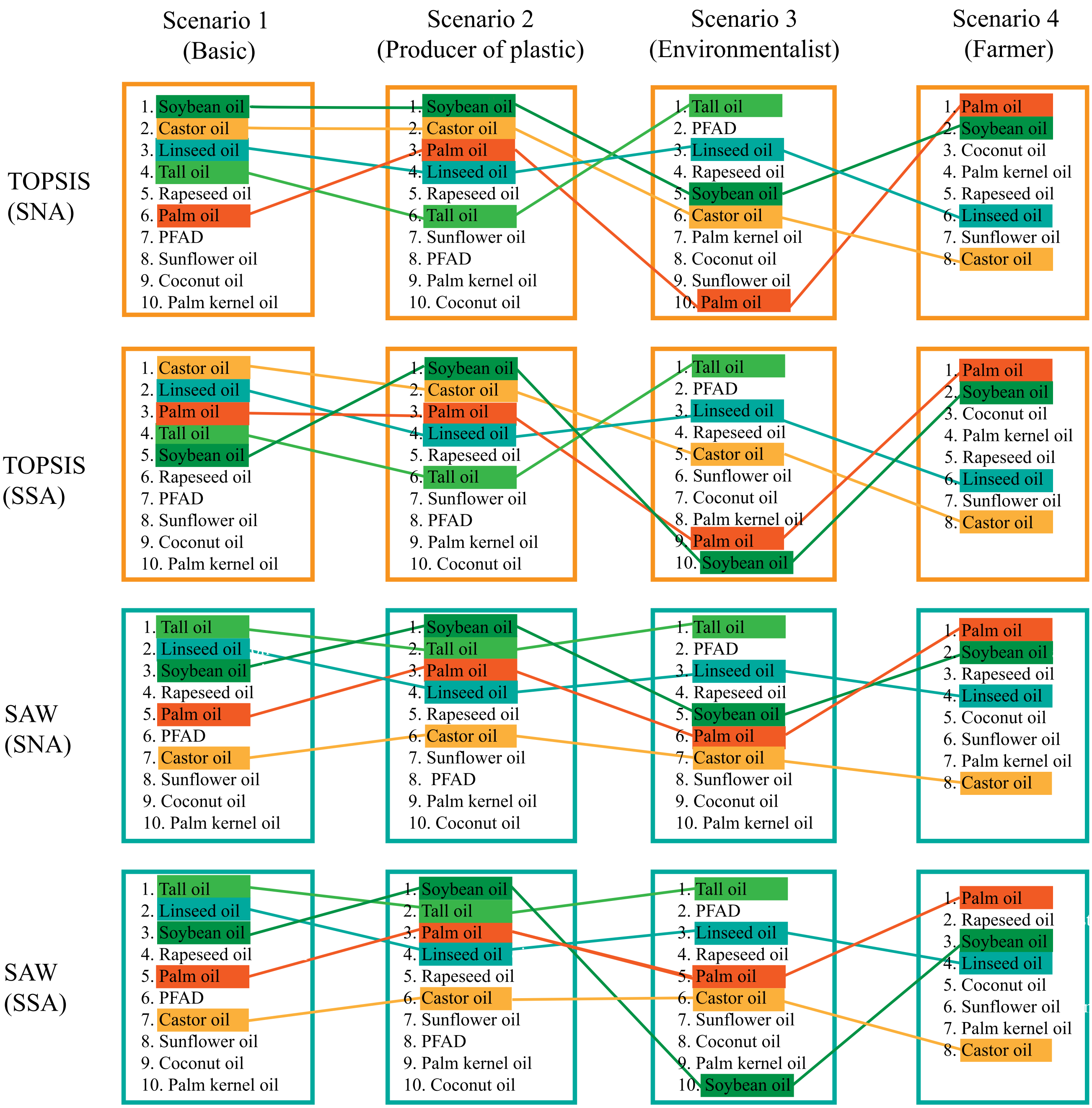

Fig. 3. A schematic representation of the differing order of ranking of raw materials across MCDM techniques, scenarios, and data sets due to the methodological differences of the applied MCDM techniques.

García-Cascales and Lamata, 2012). The differences in the order of ranking of raw materials caused by the MCDM techniques have schematically been highlighted in Fig. 3.

Despite these methodological differences, coherent conclusions can be drawn based on the obtained TOPSIS and SAW results. However, as discussed in Section 3.1, the most and least suitable performance of a raw material is always dependent on the inherent interests of the specific scenario. Additionally, the relatively high environmental impacts of the data set of SSA undermine the order of ranking of soybean oil in all the scenarios, except of the scenario 2, producer of plastic. This is especially evident in the scenario 3 of environmentalist, in which the order of ranking of soybean oil is impaired from 5 to 10 (the worst performance). In terms of the individual raw materials, in the order of precedence, tall, soybean, and linseed oil are the best performing raw materials across different scenarios according to TOPSIS and tall oil, followed by linseed and palm oil according to SAW. On the other hand, the worst performing raw materials are, in the order of precedence, palm kernel oil, followed by sunflower and coconut oil (as a shared 2nd place) in TOPSIS, together with palm kernel, coconut, and sunflower oil in SAW. Nevertheless, the environmental impacts of palm oil, palm kernel oil, and PFAD, with an effect on the MCDM results, may have been affected by the uncertainty caused by the differing allocation methods utilized in LCA.

Interestingly, castor oil performs more poorly in TOPSIS than in SAW, especially in the scenarios 1 (basic) and 2 (producer of plastic), which is most probably caused by the differing algorithm of these techniques. Simultaneously, in TOPSIS, the highest market availability of castor oil-based plastics significantly improves the order of ranking of castor oil in the first two scenarios. Castor oil also possess relatively poor general performance across differing MCDM techniques, scenarios, and data sets, which is unexpected due to its extensive use for the industrial production of many types of polyamides. On one hand, the results can be explained by the high environmental impacts of castor oil, considerably low production quantities (castor bean and oil), high price (castor oil), together with moderate performance of castor oil across the rest of the criteria. On the other hand, castor oil contains high proportions of ricinoleic acid (C18:1), being the only commercial source of this hydroxylated fatty acid for the chemical industry (Patel et al., 2016).

Consequently, as explained in Section 3.1, MCDM techniques analyse the trade-offs of alternatives among multiple criteria, the outcome of analysis indicating the overall performance of these alternatives with their inherent advantages and disadvantages. Against this background, among the well performing raw materials, tall and linseed oil are particularly interesting alternatives due to their moderate (tall oil) and high (linseed oil) chemical functionality, non-competitiveness with food production, low environmental impacts, together with excellent ability of their precursors (pine and linseed, respectively) to be cultivated on both marginal and contaminated land. Simultaneously, palm and soybean oil possess only low (palm oil) and moderate (soybean oil) chemical functionality, compete with food production, can only moderately be cultivated on marginal and contaminated land, and have either moderate (palm oil) or high (soybean oil in terms of SSA data set) environmental impacts. Therefore, the relatively low price and high production quantity of soybean and palm oil are the factors that often increase their overall performance, whereas the less-produced tall and linseed oil are superior from an ethical and environmental point-of-view.

In the end, the methodological differences of MCDM techniques, with an impact on the obtained results and their interpretation, call for the importance of careful consideration of dissimilar MCDM techniques already at an early stage of research to find out the most applicable technique for the problem to be solved. For instance, TOPSIS as a technique is more accurate in comparison to rather simple SAW, but might overestimate and even complicate the interpretation process, which may not be the most desirable outcome in some studies with, e.g., already moderately high level of uncertainty.

4.2. Framework for MCDM analysis

It is evident that data choices can influence MCDM results in the form of deficiencies of varying degrees if not dealt properly. Consequently, the points of improvement of MCDM framework in the present paper include the differing timescales of quantitative data due to the lack of accessible data. Additionally, the lack of available data may effect on the selection of the appropriate set of criteria, as well. As an example, the global yield of soybean per hectare is very low (belonging to the lowest-ranking category of 1), whereas its production quantity is considerably higher (belonging to the highest-ranking category of 9), with a positive or negative effect on the performance of soybean in the results of the MCDM analysis depending on the utilized criterion.

The lack of data also forced to make assumptions to reveal an adequately usable estimate, which may, however, to some degree distort the MCDM results. For instance, the production quantity of black liquor, crude palm oil, and PFAD were estimated based on the collected scientific papers and reports. In the similar manner, in the criterion of oil content, the content of fatty and resin acids of black liquor was collected from the scientific paper. Regarding the matter, statistical methods, such as group average and simple linear regression, were considered instead of assumptions, but neglected due to their misleading results. In the future, more advanced methodologies, such as possibility distributions, could be considered to treat uncertainty of data caused by lack of data due to the imprecise real-world information (Madi et al., 2016).

Another factor to consider is the difficulty to determine consistent and appropriate weights of the criteria (Thakkar, 2021), select an appropriate set of criteria, and utilize qualitative data prone to distortions caused by human perceptions when gathering and interpreting this type of data, a phenomenon called linguistic uncertainty (Madi et al., 2016). In this context, MCDM techniques of TOPSIS and SAW can only utilize quantitative data, which is why the qualitative or semi-qualitative data must be converted into the quantitative form by developing a specific scaling technique for this purpose. As a drawback, these scaling techniques may homogenize the obtained results, as observed in the present paper: a small difference between the upper and lower values of the applied scaling technique (e.g., 1–2–3 and 1–3–5 scaling) homogenized the obtained normalized values and, further, the results of TOPSIS. This phenomenon was solved by using the 1–5–9 scaling technique.

Consequently, to avoid these challenges caused by qualitative data, an option would be to select a MCDM technique that can utilize both qualitative and quantitative data and/or use highly accessible and comprehensive quantitative data from trustworthy sources for a reasonable number of carefully selected criteria. In the latter case, this would of course require the adequate existence of these trustworthy sources with comprehensive data sets for multiple materials, which may not always be the case, especially in terms of the less produced and researched raw materials, such as jatropha seed and jatropha oil as well as vernonia seed and vernonia oil.

5. Conclusions

In the present paper, a novel framework for multi-criteria decision-making analysis was developed and further utilized to rank and finally indicate the suitability of the selected raw materials to produce bio-based plastics. The novelty of the framework is based on the use of comprehensive set of raw materials, extensive and versatile starting data together with the newly developed criteria, stages of categorization, 1–5–9 scaling technique, and scenarios with their weights of importance. Additionally, the available qualitative and quantitative techniques are innovatively applied in constructing the MCDM framework and conducting the analysis.

As a result of the MCDM analysis, the methodological differences of TOPSIS and SAW techniques yielded slightly dissimilar order of ranking of the raw materials. This is essentially caused by differing algorithm, resulting in a dissimilar level of accuracy as well as a TOPSIS-related phenomenon, rank reversal. Despite these methodological dissimilarities, which call for a careful consideration of the suitability of the available MCDM techniques for different studies, coherent conclusions can yet be drawn. Firstly, it can be stated that the performance of an individual raw material is always dependent on the specific scenario and its weights of importance. Secondly, the relatively high environmental impacts of the data set of SSA worsen the order of ranking of soybean oil in all the scenarios, except of the scenario 2, producer of plastic. Thirdly, tall, linseed, soybean, and palm oil possess the highest overall performance across the MCDM techniques, scenarios, and data sets, whereas palm kernel, coconut, and sunflower oil show generally the most undesirable performance. Noteworthy, the results of a MCDM analysis are always a compromise with a basis on different trade-offs. Therefore, the well-performing raw materials identified in the present paper still possess their inherent advantages and disadvantages in need of a careful consideration.

In addition to the applied methodology, the developed MCDM framework may influence the results. Consequently, in the future, more appropriate weights could be assigned to the criteria by using a solid methodology. Additionally, the challenges related to the quality and reliability of data could be overcome by only using a reasonable number of carefully selected criteria with a basis on a highly accessible and comprehensive quantitative data from trustworthy sources as well as more advanced methodologies to treat and utilize different types of data and data uncertainty in general.

Finally, the present paper serves as a guidepost targeted for diverse actors of the early-stage bio-based plastics' value chain with varying point-of-views. The paper also offers a framework for analysing the features of diverse raw materials with a possibility to be utilized and further developed in the future studies. Arguably, with further developments, the novel MCDM framework can be of relevant significance in analysing the features of various raw materials to produce bio-based plastics.

CRediT authorship contribution statement

Laura Äkräs: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing – original draft, Visualization. **Marjatta Vahvaselkä:** Conceptualization, Methodology, Investigation, Formal analysis, Writing – review & editing**. Frans Silvenius:** Conceptualization, Investigation, Formal analysis. **Jukka Seppälä:** Conceptualization, Formal analysis, Project administration, Supervision, Funding acquisition, Writing – review & editing. **Hannu Ilvesniemi:** Conceptualization, Formal analysis, Project administration, Writing – review & editing.

Declaration of Competing Interest

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

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.indcrop.2022.115584.

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