Incorporating Relative Importance: selecting a polyphenol production method for agro-waste treatment in an environmental and economic multi-criteria decision making context

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Abstract

Purpose: The No Agricultural Waste project is faced with selecting the best alternative amongst six extraction methods for polyphenol production used to upgrade agricultural residues.

Methods: In order to complete this, a multiple criteria decision assessment method, Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), is applied to results for the six extraction methods from techno-economic assessment and life cycle assessment carried out previously in the project. A normalization-based method of relating the weighting applied in the MCDA to the relative importance of environmental impacts in the assessment is applied, and decision support is provided for various levels of weight given to the economic impacts of the system.

Results: One clear ideal alternative, a pressurized liquid extraction method using Ethanol, Water & $SCCO_2$ solvent with a solvent ratio of 5, is specified, along with a second best alternative using acetone and water and a solvent ratio of two. The third best alternative depend on the weight given to economic impacts and the weighting applied amongst environmental impacts.

Conclusions: It is concluded that apart from the ideal alternative and the second ranked alternative, the third ranked alternative depends on the weight given to the economic indicator. Furthermore, the application of the relative importance factor for environmental criteria as a method of deriving weighting reduced the influence of criteria with impacts that are relatively unimportant in absolute terms.

1. Introduction

When policy makers, corporations, or any other actor is faced with the need to choose between alternative solutions to a given problem, there is often a multitude of issues to be taken into account. And, the decision-making context surrounding such a choice can be handled in many ways, from community-based decision making to round table discussions or even executive fiat. However, without a tool for handling fundamentally conflicting information, the results of decision making through discussion can vary wildly and may depend on happenstance and or subjective factors. Since its primary foundation in in the 1950's, Multiple Criteria Decision Analysis (MCDA) has been applied to aid in alleviating these problems by introducing a transparent and repeatable form of decision support [1].

When looking at environmental issues in life cycle assessment (LCA), oftentimes practitioners turn to single indicators such as global warming potential (carbon footprinting), but this poses potential downfalls such as burden shifting (e.g. shifting environmental burdens from carbon emissions to environmental or human toxicity) [2]. In other cases, practitioners turn to endpoint damage modeling, but these have high levels of uncertainty and still leave the decision maker with several categories of environmental damages (e.g. ecosystem health, human heath, and resource availability). Furthermore, neither of these methods can be directly combined with economic indicators. In some cases, LCA practitioners have monetized impacts in order to combine environmental and economic indicators, however these suffer from issues, among others, involving the relationship of internalized and externalized costs [3]. These issues have lead some LCA practitioners to turn to MCDA for providing decision support [4–6].

When applying many types of MCDA, though, there is one element that has a determining effect on decision support, namely weighting. In this paper, MCDA is applied to the decision context of a European Union Horizon 2020 project, No Agricultural Waste (NoAW), choosing between various developed technologies for extracting polyphenols as a means of upgrading agricultural wastes to agricultural co/by-products. A weighting-profile derivation framework is proposed in order to incorporate the relationship between the various environmental impact criteria that are the result of life cycle assessments and an absolute reference point for environmental impacts in order to avoid making a decision based on irrelevant criteria. The criteria from LCA and an economic analysis are then incorporated to provide decision support for selecting a technology for scale-up in the NoAW project.

2. Methodology

a. Definition of the case

The NoAW project will be selecting a technology for polyphenol extraction to undergo further testing at pilot scale, after having developed a number of extraction methods at lab scale. These include both processes using acetone and ethanol as a solvent (Table 1) and are further described in [7]. Amongst these six alternative extraction methods, one must be chosen for upscaling; however, due to the potential for technical issues, a second and third choice method for upscaling should also be chosen. Attributes of the various extraction methods are available in the form of ReCiPe 2016 [8] midpoint environmental impacts and a production cost that is obtained via a techno-economic assessment.

Table 1: Description of assessed alternative extraction methods with ReCiPe 2016 midpoint impacts and production cost shown per kg of gallic acid production [7]

	Solvent Extraction				Pressurized Liquid Extraction		
	Acetone & Water		Ethanol & Water		Ethanol, Water & $SCCO_2$		
	340 ton GA/y		290 ton GA/y		572 ton GA/y		
	solvent ratio: 5	solvent ratio: 2 (dryer required)	solvent ratio: 5	solvent ratio: 2 (dryer required)	solvent ratio: 10	solvent ratio: 5	
Impact	**S-AcN-5**	**S-AcN-2**	**S-EtOH-5**	**S-EtOH-2**	**PLE-EtOH-10**	**PLE-EtOH-5**	Unit
Fine particulate matter formation	2.26E-02	1.93E-02	2.81E-02	2.08E-02	2.62E-02	1.41E-02	kg PM2.5 eq
Fossil resource scarcity	1.13E+01	8.97E+00	1.43E+01	9.87E+00	1.20E+01	6.42E+00	kg oil eq
Freshwater ecotoxicity	3.09E-01	1.77E-01	4.63E-01	2.36E-01	4.38E-01	2.24E-01	kg 1,4-DCB
Freshwater eutrophication	3.47E-03	2.56E-03	5.27E-03	3.21E-03	5.26E-03	2.75E-03	kg P eq
Global warming	3.23E+01	2.73E+01	4.24E+01	3.03E+01	3.64E+01	1.95E+01	kg CO2 eq
Human carcinogenic toxicity	4.24E-01	2.89E-01	5.69E-01	3.40E-01	5.37E-01	2.80E-01	kg 1,4-DCB
Human non-carcinogenic toxicity	8.07E+00	4.77E+00	1.23E+01	6.36E+00	1.16E+01	5.95E+00	kg 1,4-DCB
Ionizing radiation	7.36E-01	7.00E-01	1.05E+00	8.05E-01	1.41E+00	7.48E-01	kBq Co-60 eq
Land use	1.97E-01	2.23E-01	2.93E-01	2.53E-01	3.42E-01	1.85E-01	m2a crop eq
Marine ecotoxicity	4.70E-01	2.85E-01	6.98E-01	3.71E-01	6.51E-01	3.35E-01	kg 1,4-DCB
Marine eutrophication	2.30E-04	1.80E-04	3.40E-04	2.20E-04	4.00E-04	2.10E-04	kg N eq
Mineral resource scarcity	2.82E-02	1.49E-02	4.37E-02	2.09E-02	4.02E-02	2.05E-02	kg Cu eq
Ozone formation, Human health	3.50E-02	2.94E-02	4.25E-02	3.14E-02	3.82E-02	2.05E-02	kg NOx eq
Ozone formation, Terrestrial ecosystems	3.64E-02	3.03E-02	4.42E-02	3.24E-02	3.95E-02	2.12E-02	kg NOx eq
Stratospheric ozone depletion	7.62E-06	6.29E-06	1.09E-05	7.42E-06	1.10E-05	5.80E-06	kg CFC11 eq
Terrestrial acidification	6.05E-02	5.43E-02	7.21E-02	5.70E-02	6.84E-02	3.70E-02	kg SO2 eq
Terrestrial ecotoxicity	4.05E+01	3.57E+01	5.99E+01	4.21E+01	5.24E+01	2.79E+01	kg 1,4-DCB
Water consumption	1.53E-01	8.65E-02	1.69E-01	9.24E-02	2.05E-01	1.06E-01	m3
Production cost	8.6	7.9	9.5	8.6	7	4.9	€

b. Application of MCDA

In order to incorporate the various environmental as well as the economic criteria, the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method of MCDA [9] is used. This is chosen due to its previous application in the context of LCA and because it is one of the most widely applied compensatory methods of MCDA when cardinal indicators are available for all alternatives [10]. This selection is further discussed in section 4.

All midpoint indicators from LCA and production price of the various polyphenol production methods (Table 1) are used as criteria in the application of TOPSIS.

c. Development of Weighting

When applying TOPSIS, there is an inherent application of weighting, even in its default mode, equal weights are applied. This presents a problem because the selection of the ideal alternative is directly related to weighting. Ideally, this process would be completed relative to planetary boundaries [11] using an absolute relationship to impacts from LCA [12]. However, this absolute relationship is not yet well enough understood/developed, nor has it been developed to include all impact categories covered in LCA. As such, an alternative relationship must be established. This poses issues, which are further discussed in section 4.

In this case, normalization factors (NF) [13] are used to derive a relative importance factor (RIF), relating the average value, amongst all of the alternative extraction methods, of each of the midpoint impacts (MI) to the average European's annual environmental impact such that $RIF_i = \overline{MI_i}/NF_i$. The relationship between environmental and other criteria, in this case production cost, is then accounted for such that the sum of all weights is equal to 1000. The resultant weighting is then displayed in tabular form to promote full transparency in the assessment (Table 2, Table 3).

3. Results

After applying RIF, weighting strings can be derived for the application of TOPSIS with a range of importance given to economic impact from 0-1000, of 1000 available points distributed in the weighting profile (Table 2). This is also done for equal weights (EW) amongst environmental impacts and the same range of importance of economic impact (Table 3).

Table 2: Weighting strings including RIF for environmental impacts and a range of importance of economics

product production cost	Fine particulate matter formation	Fossil resource scarcity	Freshwater ecotoxicity	Freshwater eutrophication	Global warming	Human carcinogenic toxicity	Human non-carcinogenic toxicity	Ionizing radiation	Land use	Marine ecotoxicity	Marine eutrophication	Mineral resource scarcity	Ozone formation, Human health	Ozone formation, Terrestrial ecosystems	Stratospheric ozone depletion	Terrestrial acidification	Terrestrial ecotoxicity	Water consumption
0	12.83	276.36	183.72	86.75	58.98	59.26	3.93	28.40	0.61	161.97	0.86	0.004	23.98	28.77	2.05	21.34	42.57	7.62
100	11.55	248.72	165.35	78.08	53.08	53.33	3.53	25.56	0.55	145.78	0.77	0.003	21.58	25.90	1.84	19.21	38.31	6.86
200	10.26	221.09	146.97	69.40	47.18	47.41	3.14	22.72	0.49	129.58	0.69	0.003	19.18	23.02	1.64	17.08	34.06	6.10
300	8.98	193.45	128.60	60.73	41.28	41.48	2.75	19.88	0.42	113.38	0.60	0.002	16.78	20.14	1.43	14.94	29.80	5.34
400	7.70	165.82	110.23	52.05	35.39	35.55	2.36	17.04	0.36	97.18	0.51	0.002	14.39	17.26	1.23	12.81	25.54	4.57
500	6.42	138.18	91.86	43.38	29.49	29.63	1.96	14.20	0.30	80.99	0.43	0.002	11.99	14.39	1.02	10.67	21.28	3.81
600	5.13	110.54	73.49	34.70	23.59	23.70	1.57	11.36	0.24	64.79	0.34	0.001	9.59	11.51	0.82	8.54	17.03	3.05
700	3.85	82.91	55.12	26.03	17.69	17.78	1.18	8.52	0.18	48.59	0.26	0.001	7.19	8.63	0.61	6.40	12.77	2.29
800	2.57	55.27	36.74	17.35	11.80	11.85	0.79	5.68	0.12	32.39	0.17	0.001	4.80	5.75	0.41	4.27	8.51	1.52
900	1.28	27.64	18.37	8.68	5.90	5.93	0.39	2.84	0.06	16.20	0.09	0.000	2.40	2.88	0.20	2.13	4.26	0.76
1000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 3: Weighting strings including equal weighting for environmental impacts and a range of importance of economics

product production cost	Fine particulate matter formation	Fossil resource scarcity	Freshwater ecotoxicity	Freshwater eutrophication	Global warming	Human carcinogenic toxicity	Human non-carcinogenic toxicity	Ionizing radiation	Land use	Marine ecotoxicity	Marine eutrophication	Mineral resource scarcity	Ozone formation, Human health	Ozone formation, Terrestrial ecosystems	Stratospheric ozone depletion	Terrestrial acidification	Terrestrial ecotoxicity	Water consumption
0	55.6	55.6	55.6	55.6	55.6	55.6	55.6	55.6	55.6	55.6	55.6	55.6	55.6	55.6	55.6	55.6	55.6	55.6
100	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0
200	44.4	44.4	44.4	44.4	44.4	44.4	44.4	44.4	44.4	44.4	44.4	44.4	44.4	44.4	44.4	44.4	44.4	44.4
300	38.9	38.9	38.9	38.9	38.9	38.9	38.9	38.9	38.9	38.9	38.9	38.9	38.9	38.9	38.9	38.9	38.9	38.9
400	33.3	33.3	33.3	33.3	33.3	33.3	33.3	33.3	33.3	33.3	33.3	33.3	33.3	33.3	33.3	33.3	33.3	33.3
500	27.8	27.8	27.8	27.8	27.8	27.8	27.8	27.8	27.8	27.8	27.8	27.8	27.8	27.8	27.8	27.8	27.8	27.8
600	22.2	22.2	22.2	22.2	22.2	22.2	22.2	22.2	22.2	22.2	22.2	22.2	22.2	22.2	22.2	22.2	22.2	22.2
700	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7
800	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1
900	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6
1000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Applying these weightings to the criteria derived from LCA and techno-economic assessment using TOPSIS, it is possible to provide decision support in the form of a single score indicator of idealness of the various technological alternatives (Figure 1).

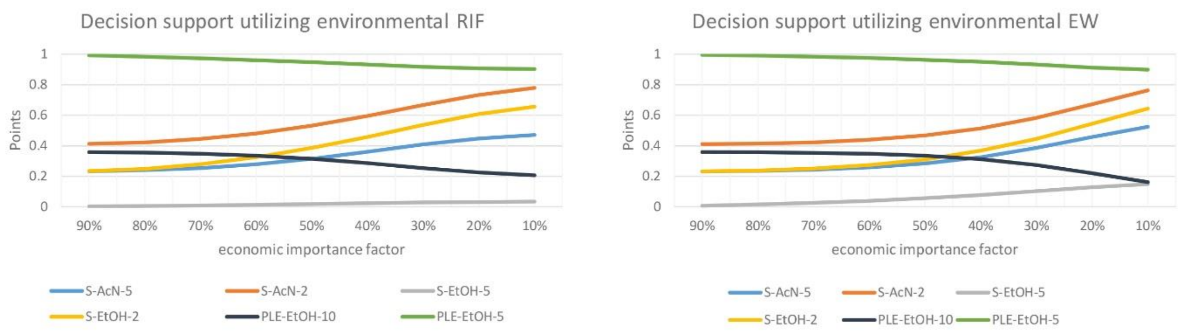

Figure 1: TOPSIS derived single score indicator of idealness (most ideal=1) for both RIF derived environmental weighting and EW environmental weighting amongst a range of EIF

4. Discussion

a. Interpretation of results

Based on the application of TOPSIS, it can be easily concluded that the PLE-EtOH-5 method outperforms all other alternative extraction methods. It is both the best economic performer and the best environmental performer in nearly all impact categories. This results in it being classified as the most ideal solution regardless of weighting. In addition, the S-AcN-2 remains the second ranked method regardless of weighting method. This indicates that these two alternatives exhibit characteristics that consistently perform better than the other alternatives. However, once one moves past the top ranked technologies, and must determine a third ranked technology, the picture becomes far less clear. The PLE-EtOH-10, and S-EtOH-2 alternatives vie for the third rank. S-EtOH-2 outperforms PLE-EtOH-10 environmentally, while PLE-EtOH-10 outperforms S-EtOH-2 economically. This results in a rank reversal as one changes the weight given to the economic criterion.

As can be seen in Table 4, there is significant range in the importance of specific environmental impacts in RIF for the assessed methods. For example, some impacts such as human non-carcinogenic toxicity, marine eutrophication, and land use are insignificant in relative importance, and mineral resource scarcity is almost entirely irrelevant. On the other hand, fossil resource scarcity and freshwater ecotoxicity make up nearly half of weighting applied to environmental impacts due to the scale of their impact compared to the other environmental criteria relative to the average European's environmental impact.

One other element of note is the difference of decision support between 40% and 70% economic importance factor (EIF) for the EW and RIF weighting. When using RIF, at 60% EIF, S-EtOH-2 and PLE-EtOH-10 are ambiguous in terms of ranking between third and fourth. Around 50% EIF, S-EtOH-2 is unambiguously ranked third when using RIF, however; when using EW, PLE-EtOH-10, S-AcN-5, and S-EtOH-2 are all ambiguous in terms of preference. This rank reversal is due to the difference in weighting for certain environmental impact categories where PLE-EtOH-10 performs similarly to S-AcN-5 and S-EtOH-2. However, despite performing similarly in some environmental categories, when the relationship to environmental importance (Table 4) of the magnitude of emissions is accounted for, the similar environmental performance of PLE-EtOH-10 is discounted in some impact categories, as it is irrelevant in relation to the scale of other environmental impacts. And, S-AcN-5 and S-EtOH-2 outperform PLE-EtOH-10 in fossil resource scarcity and marine ecotoxicity which become exaggerated in terms of influence in the decision support using RIF, relative to the decision support when using EW, due to the relative scale of the impacts in absolute terms. Furthermore, the effective removal of impacts without great relative significance by using RIF allows for greater differentiation between S-AcN-5 and S-EtOH-2, as impact categories where they perform relatively similarly, but are not of great consequence, such as mineral resource scarcity or human non-carcinogenic toxicity, are essentially removed from effecting the decision support.

Table 4: Relative weight of environmental impacts between RIF and EW weighting ($RW = W_{RIF}/W_{EW}$)

Fine particulate matter formation	Fossil resource scarcity	Freshwater ecotoxicity	Freshwater eutrophication	Global warming	Human carcinogenic toxicity	Human non-carcinogenic toxicity	Ionizing radiation	Land use	Marine ecotoxicity	Marine eutrophication	Mineral resource scarcity	Ozone formation, Human health	Ozone formation, Terrestrial ecosystems	Stratospheric ozone depletion	Terrestrial acidification	Terrestrial ecotoxicity	Water consumption
0.2309	4.9745	3.3069	1.5616	1.0616	1.0666	0.0707	0.5112	0.0109	2.9155	0.0154	0.0001	0.4316	0.5179	0.0368	0.3842	0.7663	0.1372

b. Alternative weighting methods

Another important element in interpreting the results from RIF weighting is understanding that there is a level of uncertainty in the normalization factors used to derive the RIF, and that the decision to use current emissions as a reference point does not necessarily have a relationship to the severity or consequences of environmental impacts. However, it does provide an indication of the relative importance of an emission, or reduction thereof, to the status quo. If absolute sustainability related factors were available for all relevant impact categories, the application of these instead of normalization factors would be preferable, as they would provide a stronger link to environmental impact.

An alternative to either of these methods would be to derive a RIF weighting from endpoints using e.g. monetization. While this might seem appealing, as there is a stronger connection with environmental damages when using endpoint indicators in LCA, the challenge comes in determining the relative importance of the different damage categories. This relative importance is purely subjective, and as such a specific cultural perspective would be applied to the derivation of the weighting profile. While this could be carried out in a scientific fashion to be representative of a decision maker group, the results would already contain some bias toward certain impacts introduced in the endpoint calculation [4, 6]. This would make the results more challenging to interpret and potentially lead to decision support that in the end does not reflect the true preferences of the decision maker.

c. Alternative MCDA methods

As discussed in the introduction, there are a number of potential alternatives to the use of MCDA. There are also a number of alternative methods of MCDA (other than TOPSIS) that could have been applied. Methods such as those that include preference comparison based on pairwise comparisons such as analytical hierarchy process (AHP) or outranking approaches such as elimination and choice translating reality (ELECTRE) or preference ranking organization method for enrichment evaluation (PROMETHEE). All of these methods include benefits and drawbacks, however, due to the simplicity of application as well as the easy comprehensibility of TOPSIS, it was chosen for this application. In particular, even when faced with a non-expert audience it is easy to describe how TOPSIS functions, including its relationship to weightings used in its application. This was considered a significant benefit, as it greatly increases the transparency of the application of MCDA and reduces the potential for misgivings when relaying results to non-experts.

5. Conclusions

Based on the results of both economic and environmental assessment, it can be concluded that among the tested extraction methods in the NoAW project, it is likely that the PLE-EtOH-5 alternative will perform best. However, should NoAW be unable to proceed with this technology for upscaling, then S-AcN-2 and S-EtOH-2 and PLE-EtOH-10 are all potential alternatives, depending on the importance given to economic performance versus environmental performance. In addition to the demonstrated ability of MCDA to increase the transparency and reproducibility of a decision making process, it can be concluded that the introduction of RIF as a method of deriving a weighting, relative to equal weights, for use in MCDA for LCA can likely reduce the impact of irrelevant and/or subjective criteria on the conclusions drawn from the application of MCDA that include weighting such as TOPSIS.

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