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Evaluation of bioresources validation

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Abstract. A major worldwide problem is the degradation of energy sources and the wide amount of waste products from industries, households, or from any other human activities. But what if both problems can be solved by one solution? Extensive data show that validation of bioresources increases the production of the value-added product. The assessment is based on a scenario approach. A vast literature review was performed, to investigate the alternative application pathways for various types of non-primary bioresources. Multicriteria analysis is considered as the current gold standard technique for bioresources valorisation and is proved for two cases. Firstly, we present tests that evaluate the performance of different pre-treatment methods in order to extract fibre from Hogweed biomass. Secondly, we assess the resilience of our approach using Multi-criteria analysis for brewers' spent grain to find out the best value-added product. The results demonstrate the adequacy of the method for Hogweed biomass and brewers' spent grain valorisation.

Key words: bioeconomy, biorefinery, bioresources, industrial by-products, multi-criteria analysis, valorisation pathways.

INTRODUCTION

Bioeconomy shows the link between natural resources or residues and their conversion into high-qualitative bio-based products. The industrial business and society usually consume bioresources for agribusiness, food, aquaculture, and supply their products to the market (Schmidt et al., 2012). However, each kind of bio-resources has its particular and multi-level applications (Körner, 2019) and each of these applications differs regarding economic competitiveness, environmental sustainability, and real application potential. Bioresource valorisation is indirectly connected to the field of chemistry and related sciences, which shows a significant change due to the transition of fossil to renewable feedstock (Giacobbe et al., 2018). One of the core elements of the bioeconomy is biological resources. Bioresources are renewable and natural; therefore, they are crucial in combat against major worldwide challenges such as rapid population growth, fossil resource depletion, ecological security, and climate change. Bioresources are continuously used in many sectors of the economy (Efken et al., 2016). Bioresources have made life easier for humans by providing green technologies, renewable energies, and alternative sources for various chemicals (such as botulin, maltol, quinine, salicylic acid, etc). In long term scenario, biorefinery valorisation of renewable resources plays a major role in the establishment of the bioeconomy. As a result of recent advances in biotechnological processes, industrial waste can be converted into higher value-added products (Adamowicz, 2017).

Added value can be defined in many different ways, and definitions vary according to the different criteria. For bioresource valorisation, added value means extra value created over the value that could be created during the common application. Bioresource valorisation has the potential to promote the transition to the sustainable bioeconomy through two development pathways: (1) discover the higher added value product and more profitable applications of common primary bioresources (i.e., agriculture, forestry, fishery products), and (2) discover the added value of uncommon bioresources such as by-products, unwanted biomass i.e. generate from territory cleaning and waste biomass. There is some scientific research available on the valorisation of the alternative biomass sources that represent the secondary, tertiary, and quaternary bioresources, however, various alternative bioresource applications must be considered and evaluated regarding their technical, economic, and environmental feasibility. Overall, bioresource valorisation is the pathway to reach the highest levels of bioresource transformation, this represents one of the first attempts towards sustainability and sustainable bioeconomy.

The evaluation of bioresource valorisation and the potential amount of post-industrial by-products are summarized in this research paper to determine the existing situation regarding the utilization and valorisation of these bioresources. To perform the evaluation Multi-Criteria Decision-Making Analysis (MCDA) method has been used. The aim of using this method is to determine the most profitable and environmentally feasible product by choosing the best bioresource. In other words, bioresource valorisation can implant a neutral balance between environment and economy (Dean et al., 2019).

MATERIALS AND METHODS

The main research methods are applied including literature analysis, the building of valorisation pathway schemes, the case study approach, and multi-criteria analysis. A detailed methodology protocol is described below (Fig. 1).

To investigate the possibilities to produce novel and higher added value products from underused biomass, first, the literature analysis was performed. Literature analysis focuses on the definition and applications of bioresource valorisation, as well as the identification of existing and innovative alternatives for bioresource. Secondly, an approach to build a valorisation pathway scheme for each of the assessed bioresources was introduced. The developed schemes can be further used as reference materials by the stakeholders who want to implement the valorisation of a certain bioresource. Also, the literature analysis considers the bioresource cascading approach and biorefinery approach, which are two significant tools to ensure the long-term sustainability and integrated profitability of any bioresource valorisation project.

However, the knowledge of the potential valorisation alternatives is only the first Step towards their comparison and evaluation. There are important aspects (i.e., technical, economical, and environmental) that need to be considered. In order to design an accurate scenario, knowledge of evaluation criteria and an alternative is necessary. In this study, the necessary data have been obtained from international scientific research publications.

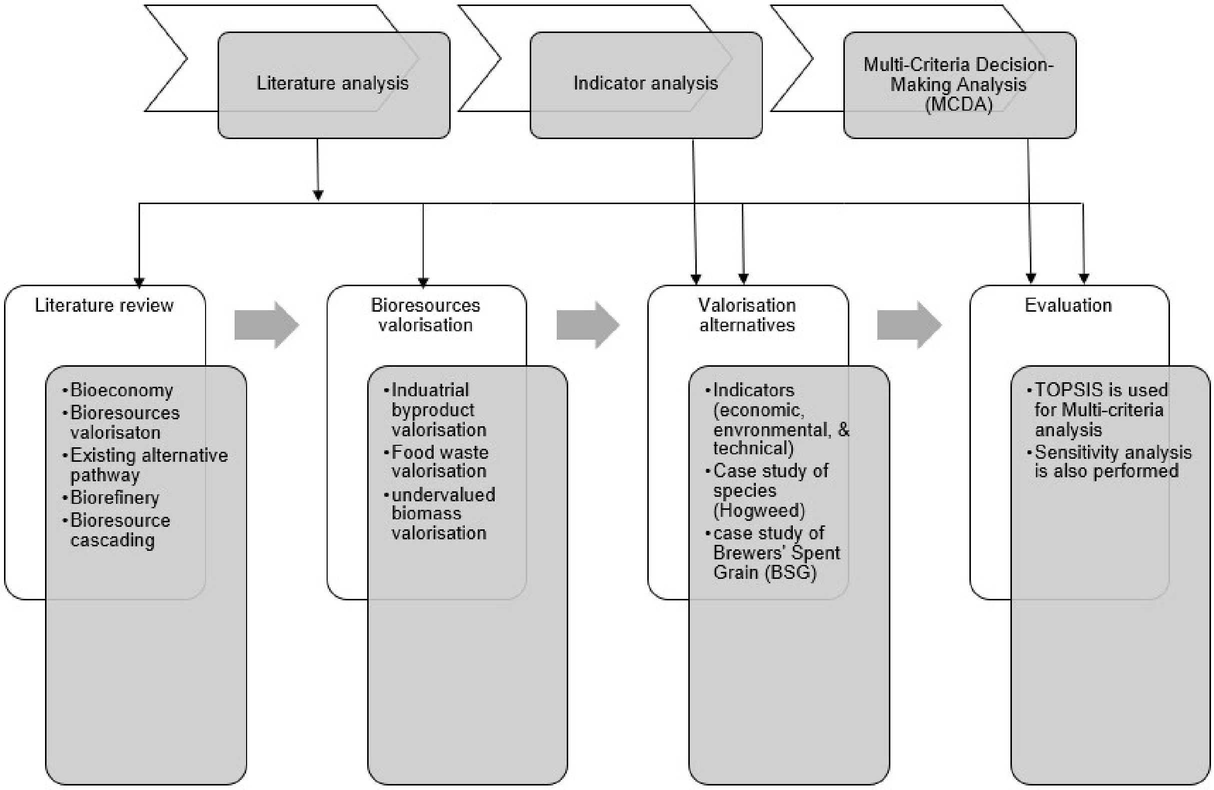

Figure 1. Methodology protocol.

Technically, Multi-Criteria Decision-Making Analysis has multiple properties that explain its application in this research. The following properties can be considered:

a) It looks to take very precise, multiple, and contrast criteria,

b) It helps to define the problem,

c) The provided model by Multi-Criteria Decision-Making Analysis gives focus and direction,

d) It gives a justifiable, manageable, and explainable decision (Belton & Stewart, 2002).

A technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is one of the classic methods used for Multi-criteria analysis (Rozentale & Blumberga, 2019). By using this method several alternatives can be compared with the chosen criteria. The reason behind using the TOPSIS method over any other method is the clarification and specification of the method. By this method, appropriate and justifiable results can be obtained in a remarkably straightforward way. One of the major advantages of this method is that it does not need any special program for evaluation (Rozentale & Blumberga, 2019). The various steps to perform the TOPSIS have been described in detail here.

Step 1: Multi-criteria analysis is used for two cases a) to determine the best pre-treatment method for hogweed invasive plant and b) to choose the best value-added product from brewers' spent grain industrial leftover by using the suitable criteria for each scenario.

Step 2: Development of decision-matrix shows the quantitative or qualitative information for each alternative and criteria. For qualitative data specifically for the TOPSIS method, it is important to derive Multi-criteria analysis scores. This score dependent on technically obtainable data. To obtain these comparative scores for qualitative data, one of the standard scales is used, for example, the Likert scale that can take values from 1 to 3 (poor, average, good performance), from 1 to 4 (very poor, poor, good, very good), or other range of scale depending on the requirements for the necessary investigation (Ward et al., 2016).

Step 3: All values obtained from the decision-matrix (Step 2) need to normalize by using the following Eq. 1.

$$r_{ai} = \frac{x_{ai}}{\sum_{a=1}^{n} x_{ai}^{2}} \tag{1}$$

where a = alternative, $a= 1,..,n$; i = criteria, $i=1,..,m$; r_{ai} = normalized criteria value.

Step 4: Eq. 2 shows the formula to calculate the weight for each criterion.

$$w_i = \frac{1}{n_i} \tag{2}$$

where w_i = weighted value; n_i = total number of criterions.

Step 5: Normalized matrix value can be derived by multiplication of normalized value (Step 3) and weight which is done by following Eq. 3.

$$v_{ai} = w_i \times r_{ia} \tag{3}$$

where v_{ai} = weighted value; w_i = weight, $w_{i1}+w_{i2}+\ldots+w_{im}=1$, $w_i=1\ldots m$; r_{ia} = normalized criterion value.

Step 6: Distance for each ideal and non-ideal alternative can be calculated by the sum of the squares of weighted criterion values (Step 5). The development of the distance measure of the ideal solution has been done by following Eq. 4.

$$d_a^{+} = \sqrt{\sum_{j=1}^{n} (v_i^{+} - v_{ai})^2} \tag{4}$$

where d_a^{+} = distance for each action to the ideal solution; v_i^{+} = ideal solution; v_{ai} = weighted value.

The development of distance for each action to the non-ideal solution has been calculated by following Eq. 5.

$$d_a^{-} = \sqrt{\sum_{j=1}^{n} (v_i^{-} - v_{ai})^2} \tag{5}$$

where d_a^{-} = distance for each action to the non-ideal solution; v_i^{-} = non-ideal solution; v_{ai} = weighted value.

Step 7: For each alternative relative closeness coefficient (Ca) is different, Ca is considered between 0 and 1; but 1 is considered as the most suitable value. Ca ratio shows the distance to the non-ideal solution, which is determined by the sum of the distance to the non-ideal solution divided by distance to an ideal and non-ideal solution. Eq. 6 shows the Equation for the relative closeness coefficient.

$$\mathrm{Ca} = \frac{d_a^-}{d_a^+ + d_a^-} \quad (6)$$

It is important to perform a sensitivity analysis for each criterion. To find out the new weight for each criterion following Equations (7 and 8) are used. Different weights distributions are changed based on the weight imposed on the distribution.

$$\beta_k' = \sum_{k=1}^{n} w' = 1 \quad (7)$$

$$w_{k1}' = \beta_k \times w', \mathrm{k} = 1,2, 3\ldots \mathrm{n} \quad (8)$$

where β_k' = the unitary variation ratio of w_k after distribution; w_k = weight being imposed on the distribution.

Case study description

The challenging task for bioresource valorisation is to determine the most appropriate pre-treatment method by which the valorisation can be done. To investigate possibilities to produce novel and higher added value products from underused biomass, Multi-criteria analysis can be applied to analyse the various alternatives.

Case study 1- pre-treatment methods and biomass

Hogweed (*Heracleum Sosnowski*) is an invasive species in Latvia, whose management methods are mostly connected to control and eradication. The only major hazard in the spread of Hogweed is the risk of damage to human health. There are preventing techniques too such as chemical-mechanical treatment. The excessively long times i.e. 2–7 years are needed for successful application of the technique (Blumberga & Zihare, 2017a). Nevertheless, in Latvia hogweed distribution is a significant problem as it covers 10,000 ha area. (Zihare et al., 2019) state that the use of invasive plant species as a type of underused bioresources is important for bioeconomy development. They also suggest that further reuse of the by-products from high added value product production should be used in a cascading or biorefinery approach to producing biofuels or energy (Zihare et al., 2019). The typical application of hogweed biomass is its use as feed for bovine animals or sheep. However, many added-value products could be made from hogweed, for example, bioethanol and biobutanol (Blumberga & Zihare, 2017a). (Zihare et al., 2018) have also investigated the production of solid biofuels in the form of pellets from hogweed. In another study (Zihare et al., 2019) identify that a large share of research on hogweed focuses on its application for food or agricultural feed. Moreover, some studies investigate its application in the pharmaceutical industry, as a fertilizer, antifungal agent, and biofuel. Cellulose can be obtained from hogweed plants and further used in cardboard production (Zihare et al., 2019). One of the potential products that can be obtained from hogweed is fibre. However, there is a lack of research on obtaining fibre from hogweed. To produce biobutanol from Hogweed a mechanical pre-treatment (milling) should be applied first to ensure access to cellulose and hemicellulose. Then enzymatic hydrolysis is applied to convert cellulose and hemicellulose to sugars and fermentation is applied to produce biobutanol. The last stage is biobutanol extraction (Blumberga & Zihare, 2017a).

Multi-criteria analysis has been done to compare and find out the most appropriate method for pre-treatment and obtaining fibres from biomass resources. The main goal to apply the pre-treatment method is to break down the cellulose fibre (Behera et al., 2014). Pre-treatment is accelerating the process and has many advantages such as:

a) Creating pores in biomass, which allows to separate cellulose, hemicellulose, and lignin residues,

b) It also enhances enzyme activity,

c) A cost-effective method in terms of low requirement of heat and power,

d) Extract the valuable component from lignin (Brodeur et al., 2011 & Behera et al., 2014).

Many pre-treatment methods can be applied for the biomass such as physical, chemical, physicochemical, and biological methods. The physical pre-treatment method requires a wide amount of energy; it also depends on the type of biomass. Due to the different porosity and particle size of each biomass physical pre-treatment method requires a different amount of energy consumption. In contrast, the biological pre-treatment method requires microorganisms like fungi, algae, bacteria, etc. to digest hemicellulose and lignin residues. The biological method also requires certain conditions at a laboratory scale, which are not costly but are time-consuming such as microbial pre-treatments. On the other side, the physical method requires less time but it requires a higher amount of energy which is not environmentally friendly (Brodeur et al., 2011). Chemical pre-treatment can be done by using various solvents. Also, this method is costly but, the most promising. Alkali pre-treatment requires a catalyst to access the process, which is expensive, while acid pre-treatment requires costly acids for recovery and specific standard equipment which can resist corrosion (Brodeur et al., 2011). An organic solvent is also one of the chemical pre-treatment methods with remarkable environmental benefits such as the requirement of low temperature and pressure, but with a high capital cost (Verardi et al., 2012).

The case study is conducted for the evaluation of different chemical pre-treatment methods for one biomass source (Hogweed). Three main criteria considered for evaluation are technical, economic, and environmental. The technical evaluation criteria include such aspects as the concentration of substrate, the time requirement for pre-treatment method, and methane generation. In terms of the economic parameter, the cost is considered as the most effective criteria, because pre-treatment scenarios involve equipment cost, maintenance cost, capital cost, the cost for catalysts, and reactors. Environmental evaluation criteria are the use of aggressive chemicals, percentage of by-products (by mass or weight), amount of wastewater, hazardous disposals, etc.

The second possibility for pre-treatment assessment is to use three biomass sources which are *Sorbaria sorbifolia* (false spirea), *Heracleum Sosnowski* (hogweed), and *Solidago canadensis* (goldenrod), and compare their properties with one pre-treatment method. The aim is to take three different biomasses and to compare the potential of maximum fibre extraction. *Sorbaria sorbifolia* species is extremely useful in the medicinal area, it is used to treat the breakdown of bones, swelling, and pain (Qu et al., 2016). However, this area of research is under widespread scrutiny and investigation. Whereas *Solidago canadensis* species has been widely observed as a decorative plant. Different parts of this plant have their specialty to produce valuable products such as flowers, leaves, and stems can produce honey, essential oils, and cellulose (Blumberga & Zihare, 2017b).

Here we compare the performance of seven different chemical pre-treatment methods considering four main criteria for Hogweed biomass. The selection of criteria has been done based on the literature analysis and availability of technical and economic information. After that, the decision-making matrix was compiled. All cost is taken into account to pre-treat 1kg of hogweed (Song et al., 2014), but for KOH cost assumption is based on the literature (Ward et al., 2016), the concentration, required amount of time (i.e. considering the total experiment time & chemical reaction between substrate and chemical), and methane generation capacity for each alternate method is assumed based on literature analysis (Amin et al., 2017). Methane generation capacity is considered a positive criterion because at the end of the process generated methane can be used for bioenergy application. The decision-making matrix, which indicates the numerical information for each criterion and alternative (Table 1).

Table 1. Pre-treatment method alternatives & selected criteria (Song et al., 2014 & Amin et al., 2017)

Criteria		Alternatives						
		NaOH Xa1	KOH Xa2	Ca $(OH)_2$ Xa3	H_2SO_4 Xa4	HCL Xa5	H_2O_2 Xa6	CH_3COOH Xa7
i1	Concentration (%)	2	2.5	2.5	2	2	3	4
i2	Time (days)	3	1	1	7	7	7	7
i3	Cost (EUR)	0.54	3	0.59	0.33	0.64	0.47	1.22
i4	CH_4 generation capacity (mL gVS^{-1})	220	295	210.71	175.6	163.4	216.7	145.1

Case study 2 - Brewers' spent grain valorisation

Due to better data availability, bioresources brewers' spent grain were selected for a case study investigation and evaluation of valorisation alternatives. To compare the alternative pathways of post-industrial bioresource valorisation three scenarios were designed for brewers' spent grain valorisation a) Biogas production, b) production of dog biscuits (feeding), and c) single-use biodegradable dishes. The selected criteria for these alternatives are environmental aspects (CO_2 emissions) and economic aspects (Net present value, capital investments).

Scenario 1 - Biogas production

For scenario 1 it is assumed that 1 ton of brewers' spent grain is used as a supplement to an existing biogas production plant. No drying of brewers' spent grain is needed before adding it into the bioreactor. The methane production yield from brewers' spent grain is 218.89 m^3 CH_4 t^{-1}, methane calorific value is 9.97 kWh m^{-3}, combustion plant efficiency is assumed to be 0.884 (Beloborodko & Rosa, 2015). Thus from 1 ton of brewers' spent grain 218.89 m^3 CH_4 can be produced with a maximal calorific value of 2,181.9 kWh and output obtainable energy of 1928.8 kWh. As brewers' spent grain is bioresource, the CO_2 emissions from the burning of bioresource-based biogas are assumed to be 0. For the economic costs of using brewers' spent grain for biogas production, it is assumed that brewers' spent grain is given to biogas plants at no cost. In detail, the transportation costs should be accounted for in each potential project separately, but to calculate the net present value of this scenario, transportation costs were assumed similar as in (Beloborodko & Rosa, 2015).

Scenario 2 - Production of dog biscuits

One of the potential higher added value applications of brewers' spent grain is the production of dog biscuits (Beer paws, 2020). The price of flour is assumed to be 1 Euro kg^{-1}, the price of peanut butter is assumed to be 13.50 Euro kg^{-1} the price of eggs is assumed to be 0.2 Euro per piece according to retail prices in May 2020. It is assumed that brewers' spent grain is available at no cost for the brewery. As the input mass of the available recipe is approximately 1kg, and the recipe provides that the outcome would be about 100 dog snacks, but it is not mentioned the outcome in weight (weight changes during cooking and drying), it is cautiously assumed that 100 dog snacks equal to 1 commercial package of dog snacks (200 g) for which a retail price of approximately 9.17 Euro per package was found in source (Beer paws, 2020). Therefore, the cost for raw material for 1 batch would be approximately 2.40 Euro, energy cost assuming small scale production (electric oven) - 1.50 Euro per batch. The labour costs are assumed to be negligible for initial assessment, considered that brewery workers could be able to do small-scale production within their day-to-day duties. CO_2 emissions from production arise due to the electricity use of an oven. As the electricity CO_2 emission factor in Latvia is reported 0.149 kg_{CO2eq} kWh^{-1} (Ferreira et al., 2019) the CO_{2eq} emissions for 1 batch of dog biscuits would be 1.3 $kg_{CO2\ eq}$. From 1 ton of brewers' spent grain, approximately 1,950 batches of dog biscuits can be produced, therefore the economic costs for raw materials and energy would account for 7,632.3 euro, the CO_2 emissions due to electricity use would account for 2,470 kg_{CO2eq}, and the profit could account to 17,881 euro. It is assumed that the production process and packaging would be manual work, the costs of packaging materials are not considered, assuming that during start-up simple packaging means could be used and distribution could be organized through breweries' in-house shops of farmers markets.

Scenario 3 - Single-use biodegradable dishes

Recently the production of single-use dishes from brewers spent grain and potato starch by hot-pressing has been reported in the scientific literature (Ferreira et al., 2019). They report that the share of brewers' spent grain can be up to 80% of the final product, but the best flexural strength in comparison to expanded polystyrene was obtained at 60% brewers' spent grain share and addition of chitosan and glyoxal. Examples of single-use plates are produced from a similar material.

Ferreira et al. (2019) report that the moisture of brewers' spent grain is 77% in their used sample, while 68% of initial moisture has been reported for a Latvian sample by (Beloborodko & Rosa, 2015). Therefore, before the hot-pressing of single-use dishes, brewers' spent grain must be dried. The energy amount that is required to dry 680 kg of water is calculated as 490.1 kWh accounting for 88.21 Euro costs if an electric drying oven is used. The requirement for dry components is calculated accordingly to the formulation given in (Regrained, 2017) From 1 ton of wet brewers' spent grain, 320 kg may be obtained. Therefore, according to the formulation, 195.73 kg of starch and 17.6 kg of glycerol would be needed, which would cost 47,0225.6 Euro considering current prices for chemicals. In the current scenario, it is assumed that the water that is further added to form the mixture is evaporated during the hot-pressing process and the mass of the end product equals the weight of dry components. If the weight of a ready plate is assumed to be 100 grams (similar to products available in retail stores (Gemoss, 2020), then around 5,333 plates can be made from 1 ton of brewers' spent grain. The hot-pressing temperature may be from 130 °C to 220 °C and the time required for pressing differs from 2 to 20 minutes (Regrained, 2017). For a cautious assumption, 10 minutes' residence time is assumed, the equipment power requirements are assumed from listings for an automatic flat heat press (Bestsub, 2020).

RESULTS AND DISCUSSION

The key findings are discussed, and recommendations are provided for future research. Firstly, the Multi-criteria analysis allows a more detailed analysis of the comparison between seven different pre-treatment methods. One of the most significant findings in the paper was the identification of the best possible method to produce a valuable product. The Multi-criteria analysis results showed that the $Ca(OH)_2$ chemical pre-treatment method is the most suitable method for pre-treatment. Based on the closeness coefficient graph is plotted (Fig. 2). The graph shows the results obtained from Multi-criteria analysis and unitary variation ratio which is ideally considered as 1. The nearest alternative to the maximum unitary variation ratio is the third alternative which is $Ca(OH)_2$. The lowest value derived is for alternative 2, which is KOH.

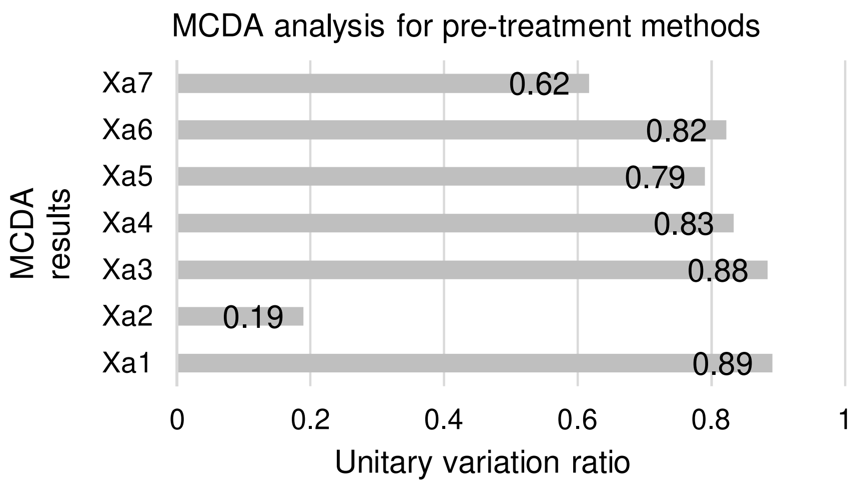

Figure 2. Multi-criteria analysis results for case study 1.

Secondly, the results for the comparison of environmental aspects (CO_2 emissions) and economic aspects (Net present value, capital investments) for all three scenarios are discussed below. As the functional unit for which the initial scenarios were calculated was 1 ton of brewers' spent grain, it is assumed as the monthly amount that a medium-sized brewery can supply. The Net present value values were calculated for all three scenarios based on taken assumptions of capital investments needed, the annual costs, and income. The labour costs were not considered, as it is assumed that a single employee could be employed for each of the scenarios, or in case that the breweries themselves develop the production of additional products them existing employees can be involved. The results of the Net present value, annual CO_2 emissions, and profit are shown below (Fig. 3). The highest CO_2 emissions are for a dog treat production, which is due to the technological process where wet brewers' spent grain is used directly in the mixture but baking of dog treats requires longer residence time in the oven, thus larger energy use and higher CO_2 emissions. On the other hand, the Net present value for dog treat production is also the highest, partly due to lower necessary capital investments and partly due to higher price of the end product (as well, a cautious assumption of half of the price found in a foreign example was used for calculations, considering the lower willingness to pay of Latvian consumers).

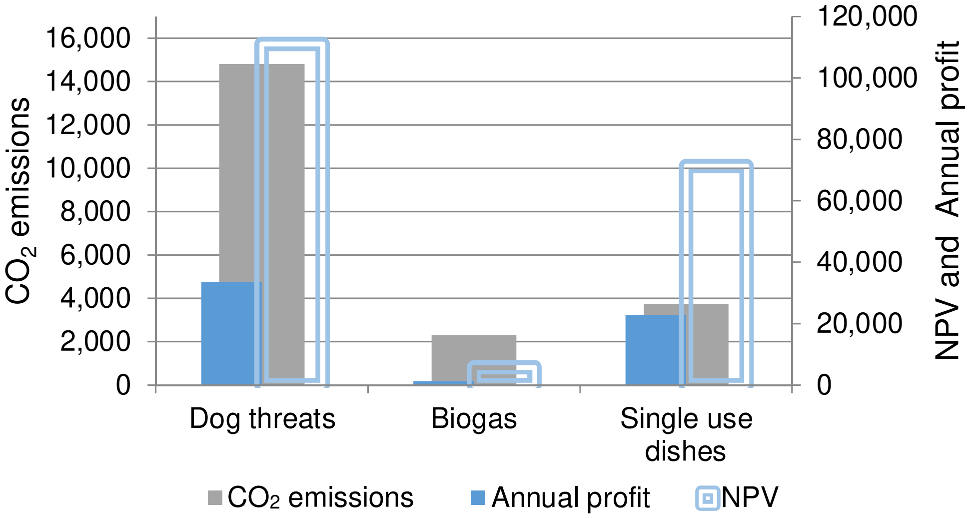

Figure 3. Scenario results for case study 2.

The biogas scenario has the lowest annual CO_2 emissions, and no capital costs are needed, but this scenario also has the lowest Net present value and annual profit, due to only small addition of added value during brewers' spent grain processing into biogas. Besides, to consolidate the effects of various evaluation criteria and provide a single value evaluation for each of the scenarios, a Multi-criteria assessment by the TOPSIS method was applied. For the Multi-criteria assessment, it is assumed that regarding capital costs and CO_2 emissions the ideal solution is minimum, while for the Net present value the ideal solution is maximum (Fig. 4). Finally, Sensitivity analysis is performed in order to check the influence of attribute distribution on the results of the TOPSIS method for both case studies.

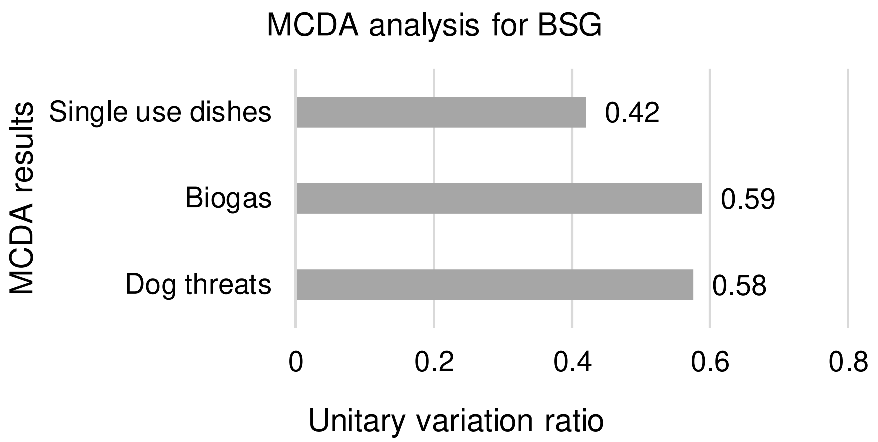

Figure 4. Multi-criteria analysis results for case study 2.

In a nutshell, the results of this work will unravel and shed light on the understanding of bioresource valorisation alternatives. However, a closer look at the literature, reveals a number of gaps and shortcomings. Since several issues remain unaddressed, a future extension is suggested for technical outlook and experiments. This study was limited to the numerical data for some biomass resources but could be extended for future work.

CONCLUSIONS

This research aims to determine an approach for the evaluation of bioresource valorisation alternatives considering various aspects that are significant for sustainable valorisation. Firstly, this objective was approached by investigating the available literature on bioeconomy, bioresource valorisation, value-added products, biorefinery. Secondly, several alternative pathways for bioresource valorisation were identified and generic schemes for the undervalued bioresources valorisation were developed. Lastly, valorisation pathway schemes have been developed for several bioresources that are by-products of industrial production and are commonly available in Latvia.

Based on the data collected from the publicly available database on the amount of post-industrial waste and by-products generated in Latvian enterprises, an analysis of the number of bioresources potentially available for valorisation in Latvia was performed, as well as this information was compiled graphically, providing an opportunity to identify areas better suited to implement valorisation of bioresources.

Within this research, a bioresource valorisation alternative evaluation is performed for the hogweed biomass pre-treatment to extract the fibre by using Multi-criteria analysis. The assessment is based on a scenario approach and a vast literature analysis was performed regarding alternative application pathways for various types of non-primary bioresources.

Another case study has been done to evaluate valorisation alternatives for brewers' spent grain to find out the best value-added product. Multi-criteria analysis results for brewers' spent grain shows that they typically applied alternative to produce biogas from brewers' spent grain achieves the highest score (0.59) in between the developed scenarios, but more innovative and higher net present value alternative scenarios of production of dog treats (0.58) and production of single used dishes (0.42) are also significant competitors. The relatively higher score for biogas production is mainly because it is already an established alternative, no significant capital costs are needed, and this scenario has the least CO2 emissions. However, the higher annual profit and net present value for the other two scenarios indicate their large economic potential, and the environmental potential could be improved if renewable energy sources would be used for technological processes. Also, Multi-criteria analysis can be further applied to the analysis of the valorisation pathways of industrial by-products such as cheese whey and by-products of grain processing.

The research concludes that bioresource valorisation alternatives can be evaluated considering various aspects that are significant for valorisation, economic feasibility as well as environmental sustainability by using a Multi-criteria analysis approach. The Multi-criteria analysis was successfully applied to case studies to evaluate the pre-treatment of hogweed to extract fibre from it and for bioproducts production from brewers' spent grain to find out the best alternative for its management after industrial processes.

However, a significant limitation for the depth of evaluation was the lack of data on technological processes and valorisation pathways for different alternatives. It is therefore suggested to perform more scientific research and experiments, especially by presenting the results in comparable dimensions, to be able to provide more precise results and to be able to evaluate more valorisation options.

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