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Evaluating hydrodynamic cavitation for increasing the biodegradability of herbal waste: A multi-criteria approach

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ABSTRACT

This paper focuses on the issue of selecting the operational parameters of the hydrodynamic cavitation (HC) that provide a maximum increase in the biodegradability of herbal waste with possibly low energy demand. To achieve this goal, the multi-criteria determination of recommended variants (MCDRV) method was applied, which allows for selecting the most advantageous HC conditions taking into account a variety of, sometimes conflicting, indicators of the process evaluation. The conventional inference methods were ineffective in identifying the recommended runs, owing to the intricate nature of the experimental data and the multitude of evaluation criteria presented in various units, as the optimal solution. Using the MCDRV method, an analysis involving multiple criteria was carried out on 21 distinct variants to select the best HC conditions that fulfill prior assumptions of the study. For searching for the best variant or variants of HC, the following criteria were defined: BOD/COD, SCOD/COD, as well as SCOD and BOD, which were maximized; in turn, COD, phenol concentration, and energy consumption were minimized. The evaluations based on both the seven-criteria and five-criteria frameworks for the 21 variants obtained in the experiment indicated that, regardless of whether the same or different values were assigned to the importance of individual criteria, certain variants were consistently not chosen as a compromise. The variant that was repeatedly selected as a compromise solution, independent of the values of the weight of individual criteria and the number of criteria, was the variant for which the HC time and the cavitation inlet pressure were 5 minutes and 3.5 bar, respectively. The multi-criteria approach indicated that such operational conditions should be recommended for the efficient HC process of herbal waste.

Keywords: hydrodynamic cavitation, herbal waste, multi-criteria approach, MCDRV method.

INTRODUCTION

Nowadays, during climate and energy crises, the issue of alternative energy sources and energy security is becoming a global issue. An innovative method, which leverages waste lignocellulosic biomass for renewable energy, may present a solution characterized by considerable energy potential [1]. Lignocellulosic biomass is sourced from agricultural waste, including herbal waste, forestry waste, and the organic fraction of municipal and industrial waste (wood, paper) [2]. Herbs are widely used in natural medicine, cosmetics, and the health food industry, leading to an increase in the generation of herbal waste (HW) [3]. Herbal waste, classified as lignocellulosic biomass, due to its physicochemical composition and significant content of organic matter, micro- and macroelements, and nutrients, can be a valuable substrate or co-substrate in the anaerobic digestion process [4]. Lignocellulosic biomass has high biogas potential, but its complex

structure can reduce its efficiency [5]. Biomass pretreatment is considered a key step in the 2nd generation biofuel production from lignocellulosic biomass. The increased biodegradability of lignocellulosic biomass resulting from pretreatment is attributed to the reduction in the degree of polymerization and crystallinity of cellulose, the partial depolymerization and solubilization of hemicellulose, and the degradation of lignin [6]. Depending on the pretreatment mechanism, these methods are categorized as physical, chemical, physicochemical, biological, advanced oxidation, and combined [7]. Lignocellulosic biomass pretreatment should be efficient, simple, and cost-effective. Advanced oxidation processes (AOPs), such as photocatalysis, ozonation, the Fenton reaction, or cavitation (both acoustic and hydrodynamic), can be effectively used for lignocellulosic biomass pretreatment, including HW [8]. Due to its economic and energy efficiency, as well as its application to various waste types, cavitation offers a promising solution for pretreatment. Hydrodynamic cavitation in environmental engineering is mainly used for water disinfection, dye removal from wastewater, and sewage sludge treatment [9–11]. In recent years, scientific reports have emerged regarding the potential application of hydrodynamic cavitation for the pretreatment of lignocellulosic biomass, e.g., brewery spent grain, sugarcane bagasse, or citrus waste [12–14]. The authors' original idea was to use hydrodynamic cavitation for the pretreatment of herbal waste [15]. Conducting research on waste pretreatment, including the pretreatment of herbal waste using hydrodynamic cavitation, leads to the obtaining of numerous parameters describing its effects. The set of obtained parameters can be complex, the individual data expressed in various units; furthermore, their values can differ greatly, which results from the units used as well as the accuracy of a measuring device. By using the specialist knowledge available in a specific area, it is possible to determine if the intention is to reach the lowest or highest values of specific metrics, thereby improving the efficiency of the process, which leads to minimized or maximized criteria, as appropriate. This results in a number of conflicting criteria characterizing the outcomes of the experiment, hindering the selection of the optimal obtained variants. The process of selecting the "best" variant from among the possible alternatives obtained in the experiment is a key issue because it enables the selection of such quantities characterizing the process (decision variables) that ensure balanced values of all analyzed process indicators [16].

Currently, there are many well-established multi-criteria decision support methods used in various decision-making problems, such as: selecting a machining process on CNC machine tools – the TOPSIS and AHP methods [17], solving selection problems in the IoT – SAW (additive scalarization with weighted criteria expressed on a point scale), TOPSIS, VIKOR (a modification of TOPSIS), and COPRAS (a modification of AHP) methods [18], assessing diesel engine performance – the AHP method [19], or generating rankings from a set of universities – the ELECTRE III method [20]. The operation and method of generating the best variants or rankings of these variants are based on different methodological foundations. However, these methods have their specificities and certain drawbacks. Variant evaluations are performed on the set of all variants, not on the set of non-dominated variants (dominated variants are clearly mathematically inferior). The AHP and ELECTRE methods employ a hidden additive scalarization mechanism for partial results, aggregating their values into a single score, which forms the basis for generating a ranking of alternatives. ELECTRE methods introduce a category of incomparable alternatives when the top-down ranking (generating alternatives from best to worst) and the bottom-up ranking (from worst to best) differ. The TOPSIS results are significantly dependent on the normalization method of the original values, leading to ambiguity in the resulting rankings. The AHP method is very labor-intensive because the decision-maker must individually evaluate the pairwise comparisons of alternatives and criteria (e.g., with 5 criteria and 10 alternatives, the number of decisions exceeds 200). In this situation, it was decided to use the original multi-criteria determination of recommended variants (MCDRV) method [21], which searches for a subset of the best variants from a subset of non-dominated variants, does not use the scalarization method at any stage of operation, is an interactive method enabling smooth change of the importance weights of individual criteria and the number of analyzed criteria, and the calculation process is automated. Owing to these properties, the MCDRV method allows for determining subsets of variants for different weight values reflecting the importance of the criteria (weights are provided directly by the expert). The MCDRV

method does not generate a ranking of variants, unlike the other methods mentioned above. It is assumed that the variants that are determined first and those that are repeated in different subsets are the best variants.

Well-defined indicators describing the effects of the process, e.g., HC, are not concurrent, but quite the opposite, because the effective course of a given technological process is shown by an increase in the values of certain parameters and a simultaneous decrease in the values of others, e.g., SCOD and SCOD/COD ratio versus COD. Indicating which variant(s) are optimal in a situation where the values of individual indicators are expressed in different units or as dimensionless quantities is an additional difficulty that researchers must face. In such cases, multi-criteria decision support methods will be helpful in selecting the "best" variant(s). To apply these methods, it is necessary to move from the metrics describing the experiment to the optimization criteria, which requires providing information on whether a given metric will be minimized or maximized. Over the last few decades, many different methods (and their modifications) have been developed that allow for the identification of the best variant(s) [17–26]. More details can be found in [32], which provides a short overview of selected methods and their applications.

The aim of the study was to apply the original MCDRV method to find the optimal values of the HC herbal waste process (inlet pressure and time) based on multi-criteria assessment using the 7th and 5th criteria with different weights of their importance. Using this approach, the future processing of HC herbal waste under industrial conditions will be energy-efficient, while ensuring the appropriate level of degradation of the lignocellulosic structure of herbal waste and an increase in its biodegradability index before its anaerobic digestion.

METHODS AND MATERIALS

Multi-criteria determination of recommended variants method (MCDRV method)

The MCDRV method is a proprietary decision-making method for selecting from a finite set of alternatives, taking into account defined criteria that can be minimized or maximized [21]. The first step of the method is to determine the alternatives that form the so-called Pareto front, i.e., non-dominated alternatives, using positive cones. The method is a multi-stage operation in which the user can enter the values of the criterion importance weights and specify the conditions for stopping the calculation process.

The MCDRV method works by iteratively narrowing the set of Pareto-optimal variants (non-dominated variants) by determining compromise variants (using the Chebyshev norm) that form a subset with significantly smaller numbers than the original set. The pseudo-code of the MCDRV method for searching for a subset of compromise variants is shown in Figure 1.

In practice, the MCDRV method is applied repeatedly to ascertain various subsets of compromise variants corresponding to different sets of weights (ω_i) that reflect the importance of individual criteria. For a better understanding of the importance of the analyzed criteria, the principle was implemented that the total of the weights should amount to 1. By comparing the contents of the obtained subsets, one can look for variants that occur in them regardless of the preferences entered by the user for the set of criteria. The method also allows for the introduction of the number of criteria considered, which significantly increases the flexibility of the multi-criteria analysis.

Hydrodynamic cavitation of herbal waste

Due to their high methane potential, herbal waste can be effectively converted into biogas through anaerobic digestion. However, due to their composition, herbal waste, as lignocellulosic biomass, is resistant to biochemical decomposition and therefore requires pre-treatment to ensure an increase in its biodegradability. The application of hydrodynamic cavitation as a method of pre-treatment for herbal waste enables a change in the structure of the lignocellulosic material, causing the breakdown of fibers and the organic matter solubilization, which consequently leads to increased biodegradability. A detailed description of the methodology and the physicochemical composition of the mixture of wastewater and herbal waste undergoing hydrodynamic cavitation (including the parameters used for multi-criteria analysis) is provided in the authors' previous article [15]. The hydrodynamic cavitation process is described by two

```
MCDRV Method Pseudocode
INPUT:
  Variants_Set  // Set of variants with criteria
  Weights  // ω weights for each criterion, sum = 1
  Max_Levels  // Number of Stage 3 repetitions
OUTPUT:
  Compromise_Subsets  // Sets of determined compromise variants

BEGIN
// -- STEP 0: Data preparation
  FOR EACH criterion IN Criteria DO
    IF criterion IS to_be_maximized THEN
      criterion_values = -1 * criterion_values
    END IF
  END FOR
// -- STEP 1: Determining the Pareto Front
  Pareto_Set = Pareto_Optimal_Solutions(Variants_Set)
// -- STEP 2: Determining the main compromise variant
  // - Step 2.1: Ideal Point (IP) Fo
  IP_Fo = Calculate_IP(Pareto_Set) // min values for each criterion
  // - Step 2.2 & 2.3: Determining the F* variant using the Chebyshev norm
  F_star = Calculate_Chebyshev_Compromise(Pareto_Set, IP_Fo, Weights)
    Compromise_Subsets.Add(F_star)
// -- STEP 3: Determining further compromise
  Current_Pareto_Set = Pareto_Set.Remove(F_star)
  Current_IP = IP_Fo
  FOR level FROM 1 TO Max_Levels DO
    New_IP_List = []
    // - Step 3.1: Determining new IP Fo_i
    // Replacing the ith component of the IP with the component from the F* variant
    FOR i FROM 1 TO Number_Of_Criteria DO
      Fo_i = Create_New_IP(Current_IP, F_star, index=i)
      New_IP_List.Add(Fo_i)
   END FOR
    // - Step 3.2 & 3.3: Partitioning into subsets and new compromise variants
    FOR EACH Fo_i IN New_IP_List DO
      // Selection of variants not better than the new IP
      Subset_i = Filter_Variants_Not_Better_Than(Current_Pareto_Set, Fo_i)
      IF Subset_i IS NOT EMPTY THEN
        F_star_i = Calculate_Chebyshev_Compromise(Subset_i, Fo_i, Weights)
        Compromise_Subsets.Add(F_star_i)
      END IF
    END FOR
    // Optional repetition (3.1') for large sets
    IF User_Wants_More_Levels THEN
      Continue
    ELSE
      Break
   END IF
  END FOR
  RETURN Compromise_Subsets
END
```

Figure 1. Pseudocode of the MCDRV method

decision variables: x_1 – inlet pressure to the cavitation zone and x_2 – process duration, which corresponds to the count of passes through the cavitation zone. Cavitation effects are characterized by a variety of chemical and physical parameters, the values of which are expressed in various units, and their values may vary significantly (Table 1). These values may be employed to develop dimensionless indices that will function as the criteria for measuring the process effectiveness. A criterion refers to a quantity that describes the object under examination, which should ideally be minimized or maximized. From the quantities assessed regarding the hydrodynamic

cavitation process of herbal waste, 7 criteria were formulated. Criteria weighting factors were established based on technological priorities. According to the expert knowledge, the criteria chosen for multi-criteria evaluation were as follows: C1 – BOD/COD (MAX.) – the ratio BOD to COD describing the degree of biodegradability (i.e. biodegradability index), C2 – SCOD/COD (MAX.) – the ratio of the dissolved COD fraction to total COD describing the proportion of the dissolved fraction in total COD, C3 –SCOD –the dissolved organic fraction expressed as SCOD (MAX.), C4 – COD value (MIN.), C5 – BOD value (MAX.), C6 – concentration of phenols (MIN.) and C7 – total energy consumption resulting from hydrodynamic cavitation (MIN.). Another analysis was carried out that involved 5 criteria from among those previously selected: C1, C2, C4, C6, and C7.

RESULTS AND DISCUSSION

The MCDRV method was used to evaluate the results obtained in the HC herbal waste process. Analysis was conducted in a criteria space, searching for the variant(s) that could be recommended as the best for further applications. Based on the variant information, one can move to the decision variable space (inlet pressure x_1 and time x_2, Table 1) and thus obtain the desired values necessary to conduct the HC process. The analysis covered 21 variants, and the data are presented in Table 1. The seven criteria and five criteria evaluations were performed to demonstrate the adequacy of the method.

Seven-criteria analysis

This analysis considered all criteria defined in the HC herbal waste process (Table 1). In the first stage, the Pareto front was determined. The number of non-dominated variants was 16 (Table 2, col. B), listed in column C. Three analyses were performed for different sets of weights: (1) identical weights for all criteria (No. 1, col E), (2) for the weights that significantly reduced the importance of criteria C4 and C5 (No. 2, col E), and (3) for the weights that significantly increased the importance of criteria C1 and C7 (No. 3, col E). The generated subsets of compromise variants are included in column F.

Explanation of the results obtained from the MCDRV method – for example, line no. 4. In the first loop, variant no. 3 was determined. After withdrawing this variant from the set of Pareto-optimal variants, determining new ideal points, and assigning the remaining variants to them, in the second loop, further compromise variants were determined: no. 2 and 10 (when the size of the criteria space is greater than 2, the subsets are not disjoint, hence variant no. 2 appears twice in this case). In the third loop, variant no. 15 was determined. Note that when the number of elements in a subset is too small (in the extreme case, the set is empty), no compromise variant is generated.

Five-criteria analysis

The 5-criteria analysis included the following criteria: C1, C2, C4, C6, and C7, while omitting criteria C3 – SCOD and C5 – BOD. The first analysis (row 4, Table 2) was performed for identical weight values for all criteria (col. E). The determined Pareto front included 13 variants (col. B), specified in col. C. The second analysis (row 5, Table 2) was performed for weights that favored criteria C1 and C2. In this analysis, the existing Pareto front was reduced to 8 variants by applying an additional procedure that examined the local neighborhood of individual variants with a deviation tolerance within 5% of the value of the analyzed variant [34]. Two subsets of compromise variants were generated for different sets of weights, presented in col F (lines 4 and 5).

Based on the results obtained, it was shown that, in the case of a seven-criteria analysis for an inlet pressure of x1 = 3.5 bar, the system generated three compromise variants: v2, v3, and v4. For the inlet pressure x1 = 5 bar, the largest number of compromise variants was generated (from v9 to v12 and v14), whereas for x1 = 7 bar, the system generated only two variants – v16 and v17. The selected compromise variants in the following analyses demonstrated that the durations of the hydrodynamic cavitation process ranged between 2 and 60 minutes, excluding the time x2 = 45 minutes. In the case of the five-criteria analysis for x1 = 3.5 bar, the system generated two variants, v2 and v3; for x1 = 5 bar, v8 and v10; whereas for x1 = 7 bar, only one variant, v15, was generated. The results obtained (Table 2) indicate that the most frequently occurring variant in both the seven- and five-criteria analyses was variant

Table 1. Criteria and values of decision variables associated with the hydrodynamic cavitation process

Variant number	Criterion specification							
	C1 –MAX.	C2 –MAX.	C3 –MAX .	C4 –MIN.	C5 –MAX .	C6 –MIN.	C7 –MIN.	x_2
	BOD/ COD	SCOD/ COD	SCOD	COD	BOD	phenols	Total energy consumption	Time
	-	-	mg dm^{-3}	mg dm^{-3}	mg dm^{-3}	mg dm^{-3}	kWh	min.
	Inlet Pressure 3.5 bar (x_1)							
v1	0.36±0.09	0.71±0.09	2720±241.8	3837±515.1	1380±245.2	40.8±1.57	0.0000	0
v2	0.37±0.02	0.79±0.11	2990±239.5	3803±497.5	1391±212.9	41.0±1.68	0.0007	2
v3	0.46±0.04	0.83±0.10	3104±228.1	3740±480.5	1718±238.9	42.4±1.58	0.0037	5
v4	0.47±0.08	0.88±0.08	3216±238.7	3640±492.5	1699±201.7	43.5±1.79	0.0136	10
v5	0.42±0.07	0.92±0.12	3257±249.1	3570±452.1	1499±198.8	43.9±1.80	0.1295	30
v6	0.42±0.06	0.96±0.11	3313±248.5	3437±398.5	1452±186.7	46.2±1.75	0.2918	45
v7	0.43±0.07	0.92±0.09	3173±229.6	3447±397.6	1478±182.2	46.7±1.87	0.5190	60
	Inlet Pressure 5 bar (x_1)							
v8	0.26±0.09	0.50±0.11	2476±212.2	4951±298.1	1269±210.2	37.5±1.45	0.0000	0
v9	0.27±0.07	0.50±0.08	2444±207.6	4858±277.6	1329±195.8	37.8±1.50	0.0008	2
v10	0.27±0.04	0.53±0.09	2554±209.5	4863±285.4	1303±201.4	39.9±1.52	0.0048	5
v11	0.28±0.05	0.53±0.10	2568±210.5	4813±264.7	1352±204.6	41.9±1.49	0.0190	10
v12	0.28±0.06	0.58±0.08	2689±200.9	4676±225.4	1317±213.5	43.8±1.47	0.1715	30
v13	0.28±0.06	0.56±0.09	2651±212.6	4744±298.1	1345±209.9	44.6±1.39	0.3863	45
v14	0.32±0.08	0.61±0.12	2595±215.9	4257±278.9	1349±210.1	45.1±1.42	0.6870	60
	Inlet Pressure 7 bar (x_1)							
v15	0.22±0.03	0.43±0.09	2505±199.6	5800±205.2	1280±171.3	35.5±1.38	0.0000	0
v16	0.23±0.05	0.40±0.07	2319±197.5	5733±207.9	1297±118.5	36.3±1.35	0.0012	2
v17	0.23±0.04	0.42±0.09	2424±195.7	5724±210.1	1305±116.9	36.5±1.40	0.0064	5
v18	0.23±0.05	0.44±0.10	2489±198.2	5684±209.5	1331±202.2	40.2±1.65	0.0257	10
v19	0.24±0.06	0.45±0.09	2529±189,5	5661±204.5	1364±199.5	41.5±1.35	0.2315	30
v20	0.24±0.03	0.47±0.08	2575±192.4	5531±203.1	1382±189.5	42.7±1.39	0.5205	45
v21	0.26±0.04	0.53±0.11	2680±189.9	5294±201.9	1395±190.5	44.5±1.42	0.9250	60

Note: The quantities x_1 (inlet pressure) and x_2 (time) are decision variables that were adopted in the HC experiment process.

v3, with inlet pressure to the cavitation zone of x1 = 3.5 bar, and the process duration x2 was 5 min. An analysis of the subset contents of the compromise variants indicated that v3 was the sole variant present in each subset, regardless of the weighting applied. This evidence shows that this variant is the most resilient to the weight values that reflect the importance of specific criteria, making it the superior option.

The pretreatment of lignocellulosic biomass is a highly complex process, as it must facilitate the release of sugars or the breakdown of complex organic matter while keeping energy consumption, the formation of inhibitors, costs, and environmental impact under control. Szaja et al. [35] analyzed the possibility of using hydrodynamic cavitation as a method of pretreatment for coffee waste intended for subsequent anaerobic digestion. A multi-criteria analysis was used to select the most favorable conditions for the cavitation process. The main evaluation criteria were increases in biodegradability and energy consumption. The results of the multi-criteria analysis showed that the most favorable variants involved a pressure of 5 bar and a duration of 20 or 30 minutes, depending on the weightings applied. Microwave pyrolysis is one of the methods used for the pre-treatment of lignocellulosic biomass [36]. This study investigated the effect of microwave power on the pyrolysis characteristics of sawdust. However, the MCDA method used showed that the increase in energy costs resulting from higher microwave power is fully offset by improved pyrolysis efficiency. The aim of the study by Zdeb

Table 2. Compromise variants generated using the MCDRV method

Col.	A	B	C	D	E	F
No.	Number of criteria	Pareto number	Elements of the Pareto set	Analysis type	Weight	Compromise variants*
7-criteria analysis, numbers of criteria used: C1-C7						
1.	7	16	1 – 12, 14–17 none 13, 18–21	Min-Max	The same 7 x 0.1429	2 / 16, 11 / 17, 14, 9, 3
2.	7	16	as above	Min-Max with weights	0.2; 0.2; 0.1; 0.05; 0.05; 0.2; 0.2	3 / 15, 12, 17 / 16, 4, 10, 11
3.	7	16	as above	Min-Max with weights	0.25; 0.15; 0.1; 0.1; 0.05; 0.1; 0.25	3 / 15, 12, 17 / 16, 4, 10, 11
5-criteria analysis, numbers of the criteria used: C1, C2, C4, C6, C7						
4.	5	13	1–10, 15–17 none 11–14, 18–21	Min-Max	The same 5 x 0.2	3/ 2(3x), 10 / 15
5.	5	8** UI = 5%	1–5, 8, 9, 15 none 6, 7, 10–14, 16–21	Min-Max with weights	0.25; 0.25; 0.15; 0.15; 0.20	3 / 15, 8

Note: * The '/' sign indicates that the variants were determined in a subsequent loop of the MCDRV method. ** Number of the Pareto set has been reduced by additional analysis examining the proximity of the elements that make up this set [33, 34], UI – undifferentiation interval.

et al. [37] was to determine the best pretreatment conditions for *Pennisetum hybrid* in order to optimize the methane production process in terms of environmental, technical, and economic aspects. According to the results of the multi-criteria analysis, it was found that the most favorable solution in terms of most of the analyzed indicators was mechanical pretreatment involving the fractionation of lignocellulosic biomass to a particle size of <0.18 mm. In turn, Vamza et al. [38] carried out a multi-criteria analysis of lignocellulose pre-treatment processes in order to identify the best method. To compare different pre-treatment methods, scientific studies were selected in which similar lignocellulosic biomass was used. The comparison criteria were established on the basis of data available in the literature. Three main criteria were taken into account: time, cost, and process efficiency. Based on the multi-criteria analysis, it was concluded that the most preferable option for the pre-treatment of lignocellulosic biomass, such as maize stalks or sugarcane, is microbiological treatment, as it demonstrated the closest approximation to the optimal solution. From the technological point of view, the obtained results indicate that the pretreatment of herbal waste using hydrodynamic cavitation increases its biodegradability, which may enhance the efficiency of its subsequent conversion via anaerobic digestion. However, it is important to determine the optimal conditions for carrying out the pretreatment. Of the inlet pressures and cavitation time intervals analyzed, the most favorable results were obtained at an inlet pressure of 3.5 bar during the first 5 minutes of the pre-treatment process. For these operating parameters, a biodegradability degree of 0.46 was achieved, and the lowest specific energy consumption and the highest cavitation efficiency—in the form of organic matter expressed as SCOD—were observed. On the other hand, hydrodynamic cavitation used as a pretreatment method for herbal waste prior to its biological processing may generate byproducts such as phenols, which have an inhibitory or toxic effect on the microorganisms carrying out the fermentation process. The greatest increase in phenol concentration was recorded at an inlet pressure of 7.0 bar (from 35.5 to 44.5 mg dm^{-3} after 60 minutes). For lower inlet pressures, the increase in phenol concentration after 60 minutes of the process was 15% and 20% for 3.5 and 5.0 bar, respectively. At an inlet pressure of 3.5 bar, the increase in phenol concentration during the 5-minute process was approximately 3.8% and increased with the duration of cavitation. Thus, an inlet pressure of 3.5 bar and HC time of 5 minutes of HC were accompanied by the best HC effects regarding maximization of the values of parameters reflecting an increase in solubilization and biodegradability index with the simultaneous minimization of energy consumption. Regardless of whether the analysis concerned 5 or 7

criteria and whether the same or different values of weights were adopted, the same recommended variant was obtained.

CONCLUSIONS

It should be clearly stated that the adopted criteria (minimized and maximized) should accurately reflect the technical, physicochemical, and economic parameters of the HC. Although a single variant recommended among the investigated pretreatment variants may depend largely on the selected criteria, their weights, and the specific type of feedstock, a comprehensive/multi-stage multi-criteria assessment provides significant information about the process. The MCDRV method proved very effective, providing clear information on the best inlet pressure and HC time values that should be used to achieve the best final process values expressed by the defined set of criteria.

In the first stage, the MCDRV method allowed for the elimination of dominated variants – by nearly 25% in the 7-criteria analysis, and by over 35% in the 5-criteria analysis. The rejected variants (7-criteria analysis) primarily included those for which the process pressure was the highest (7 bar) and long HC times were used (from 10 to 60 minutes). In the analysis with the 5 criteria, variants with long HC times (over 10 minutes) and higher HC pressures (5 and 7 bar) were eliminated. Overall, the obtained results indicate that the process costs represented by criterion C7 (energy consumption) are very significant. This reduced the number of variants analyzed in subsequent stages of the method, distinguishing the MCDRV approach from the methods described in [17-20].

In the next stage, a subset of compromise variants was determined, the number of which did not exceed 50% of the subset of non-dominated variants, significantly simplifying the analysis and interpretation of the obtained results. These subsets did not include variants obtained for long HC times (from 30 to 60 minutes). Comparison of the generated compromise variant subsets shows that variant 3 ranks first in four different analyses, using both the 7-criteria and 5-criteria analyses, regardless of whether the same or different weight values are considered. A clear trend was observed, with variants often recurring, resulting from short HC times. Based on the results of the MCDRV evaluation, variant 3 should be recommended as the best among the investigated variants.

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