Analysis of the energy recovery possibilities of energy from lavender straws after a steam distillation process

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Abstract. In recent years, the area sown with lavender has increased in Bulgaria, which is then processed to essential oils by steam distillation. Plant residues after the steam distillation process are a major environmental problem and, at the same time, a valuable source of biofuels. Thus, the processing of lavender waste solves the problem of environmental pollution and generates energy that can be used for various purposes. This paper analyzes the possibilities for obtaining energy from lavender biomass. The processes of direct combustion and pyrolysis with their advantages and disadvantages are analyzed and the yields of the obtained products are predicted by analytical calculations. For the purposes of this study, an experiment was conducted to determine the pyrolysis products of lavender straws and their quantitative ratios, which were compared with analytical calculations. The results show that the energy obtained can ensure the implementation of the steam distillation process and the residual energy can be used for other purposes.

1. Introduction
In recent decades, both the processing and the use of biomass as a fuel in various industries, in households and in transport have increased. The reason for this is Directive 2009/28 / EU on renewable energy (recast in December 2018), which establishes a comprehensive policy for the production and promotion of energy from renewable sources and requires the EU to meet at least 20% of its total energy needs with energy from renewable energy sources until 2020.

Lavender oil is one of the most common essential oils in the world. Bulgaria has joined France as a world leader in its cultivation and production of lavender oil for several years. By 2019 the areas sown with lavender in Bulgaria are 18,000 ha according to the data presented in [1].

The extraction of lavender essential oils is carried out by a distillation process. In Bulgaria the method of steam distillation is used, which is extremely energy intensive. In the agricultural areas where the distilleries are built, near the areas sown with lavender, the sources of energy for the steam generator are electricity from the national power grid or oil. This contributes to the high cost of the final product and additional environmental pollution.

In the aspect of the above, the processing of the waste straws of lavender after a process of steam distillation to extract the essential oils in it leads to the utilization of energy in them, cheaper the final product and protection of the environment from pollution.

Data for processing biomass of different types and comparing the methods for obtaining energy from it were found in the literature [2, 3, 4, 5]. No data for the treatment of waste lavender stalks by pyrolysis and comparison with other methods for obtaining energy from them were found.

The main goal of the present study is to analyze lavender straws as a source of energy. This
requires an assessment of their properties, which define them as fuel.

In order to determine the energy potential of biomass, it is necessary to establishe its energy value. As an indicator of the energy contained in biomass is often used the HHV. The atomic ratio [6] to estimate the HHV of fuels is used.

When the ratio of cellulose, hemicellulose and lignin in the biomass is known, its behavior during pyrolysis can be predicted [7], [8] and [9].

Another important point is to determine the yields of pyrolysis products. This can be done analytically or experimentally [10, 11, 12, 13].

The thermochemical (pyrolysis, gasification, esterification and direct combustion) way of conversion of biomass into liquid, gaseous and solid fuel is analyzed, comparing only pyrolysis and combustion.

This study analyzes the properties of biomass and the products of its processing into secondary fuels, which characterize them as such. For this purpose, literature data were used: for proximate and ultimate analysis of waste lavender stalks as biomass [14], [15]; for analytical models of the share distribution of biomass pyrolysis products [8], [10], [11] and [12]; for the composition of the obtained biogas; for analytical dependences for the determination of HHV and LHV on lavender straws and biomass pyrolysis products [11], [13]; for analytical energy balance models [6], [11], [13]. The process of processing the lavender waste straws by pyrolysis was experimentally studied, and a gas analysis of the obtained biogas was performed in order to compare the predicted results of the analytical calculations.

2. Materials, methods and data used

2.1. Analytical research.

Next equations presents some of the models proposed in the literature for analytical determination of the proportions of the products of biomass pyrolysis.

Models for determining the shares of individual products [8, 10, 11, 12]:

\[ Y_{\text{char}} = Y_{\text{char,ce}} + Y_{\text{char,hc}} + Y_{\text{char,lg}} \]  

\[ Y_{\text{vol}} = 1 - Y_{\text{char}} \]  

\[ 1 = g_{\text{vp}} + g_{\text{gas}} + g_{\text{char}} \]  

\[ g_{\text{vapor}} = \frac{W}{100} \]  

\[ g_{\text{char}} = (1 - g_{\text{gas}}) \left(1 - \frac{W}{100} - \frac{A}{100}\right) + \frac{A}{100} \]  

\[ g_{\text{gas}} = g_{\text{gas}}^0 \left(1 - \frac{W}{100} - \frac{A}{100}\right)^{\frac{1}{2}} \]  

\[ Y_{\text{HF}} = Y_{\text{HF,ce}} + Y_{\text{HF,hc}} + Y_{\text{HF,lg}} \]  

\[ Y_{\text{CH}} = Y_{\text{CH,ce}} + Y_{\text{CH,hc}} + Y_{\text{CH,lg}} \]  

\[ Y_{\text{CO}} = Y_{\text{CO,ce}} + Y_{\text{CO,hc}} + Y_{\text{CO,lg}} \]  

\[ Y_{\text{H}} = Y_{\text{H,ce}} + Y_{\text{H,hc}} + Y_{\text{H,lg}} \]  

\[ Y_{\text{O}} = Y_{\text{O,ce}} + Y_{\text{O,hc}} + Y_{\text{O,lg}} \]  

\[ Y_{\text{N}} = Y_{\text{N,ce}} + Y_{\text{N,hc}} + Y_{\text{N,lg}} \]  

\[ Y_{\text{S}} = Y_{\text{S,ce}} + Y_{\text{S,hc}} + Y_{\text{S,lg}} \]  

\[ Y_{\text{HHV}} = 0.352C + 1.162H - 0.111O + 0.063N + 0.105S \]  

\[ Q_{\text{HHV}} = 0.349C + 1.178H - 0.103O - 0.015N + 0.101S - 0.021A \]
\[ Q_{\text{HHV}} = 0.341 \cdot C + 1.323 \cdot H - 0.120 \cdot O - 0.12 \cdot N + 0.68 \cdot S - 0.015 \cdot A \text{ [MJ/kg]} \] (11)

\[ \text{LHV} = 0.127 \cdot CO + 0.108 \cdot H_2 + 0.358 \cdot CH_4 \text{ [MJ/m}^3\text{]} , \] (12)

where (9), (10) and (11) are for biomass and (12) is for gas.

On the other hand, the expression for LHV of biomass, taking into account its working humidity, acquires the form [18]:

\[ Q_{\text{LHV}} = (1-W_{wb}) \cdot Q_{\text{HHV}} - 2.447 \cdot (W_{wb} + 9 \cdot (1-W_{wb}) \cdot H) \text{ [MJ/kg]}, \] (13)

where: H-mass fraction of hydrogen in the dry biomass.

Next equations presents the energy balance models [6, 11, 13].

\[ A \cdot c_p a T_0 + F \cdot c_p f T_0 + W \cdot H_0 + F \cdot HHV + Q_{\text{ext}} = (c_{CO} \cdot g_{CO} + c_{CO_2} \cdot g_{CO_2} + c_{CH_4} \cdot g_{CH_4} + c_{H_2} \cdot g_{H_2} + c_{O_2} \cdot g_{O_2} + c_{N_2} \cdot g_{N_2}) \cdot T_0 + (1-x_g) \cdot W \cdot H_g + P_c \cdot q_c + Q_{\text{gasif}} + Q_{\text{loss}} + Q_{\text{product}} \] (14)

\[ Q_{\text{gas}}^{\text{gas}} = c_{\text{gas}}^{\text{gas}} \cdot (T_{\text{pyr}} - t_0) + c_{\text{steam}}^{\text{steam}} \cdot (T_{\text{pyr}} - t_0) \] (15)

\[ Q_{\text{char}}^{\text{char}} = c_{\text{char}}^{\text{char}} \cdot (T_{\text{pyr}} - t_0) \] (16)

\[ Q_{\text{pyr}} = \Delta H_h + \Delta H_f \] (17)

\[ \Delta H_f = m_{\text{tyre}} \left( 553 - 3142 \cdot \mu_{\text{char}} \right) \] (18)

where: F - the amount of fuel; A - the amount of air; W - the amount of steam; P - the quantity of char produced; Q_{gasif} - the net heat of the reaction; Q_{loss} - total heat loss; q_c - heat of combustion of char; (1-x_g) W - the part of the steam remaining in the gas which leaving the reactor; H - enthalpy; c - specific heat.

2.2. Experimental studies of the biomass pyrolysis process.

The laboratory system is shown in figure 1.

The main purpose of the experimental part is to obtain process data that are missing in the literature. To achieve this goal, an experiment was conducted in which the waste lavender stalks were subjected to pyrolysis after a steam distillation process.

A discrete amount of feedstock is placed in the pyrolysis reactor and heated. The vapor obtained from the decomposition of the raw material leaves the system by passing through a cooler and a hydro-seal, which does not allow atmospheric air to enter the system.

\[ \text{Figure 1. Schematic diagram of the experimental setup: 1 – Pyrolysysis reactor; 2 – Heat exchanger; 3 – Liquid tank, 4 reservoir - hydraulic shutter.} \]

The experiment was performed at a reactor temperature of 350 - 400°C. The amount of gas, pyrolysis oil and solid residue obtained after completion of the experiment is taken into account. The resulting pyrolysis gas is analyzed to determine its elemental, qualitative and quantitative composition.
3. Results and discussions

3.1. Conversion processes.
As part of this study, a technical and environmental assessment was developed for two of the thermochemical methods of treatment of lavender waste: direct combustion and pyrolysis.

3.2. Structure and chemical composition of biomass from lavender stalks.
Lavender grown in Bulgaria (Lavandula angustifolia mill) is a traditional type of lavender.

The content of cellulose, hemicellulose and lignin differs significantly when comparing their content in the flowers and stems of lavender after the distillation process - table 1.

Table 1. Content of lignin, cellulose and hemicellulose in spent lavender stalks according to [14].

| Composition   | Summer | Winter |
|---------------|--------|--------|
| Biomass        | Leaf   | Leaf   |
| Mass fraction of lignin (dry basis) % | 17.1±2.7 | 21.7±0.5 |
| Mass fraction of cellulose (dry basis) % | 19.9±0.8 | 13.1±1.4 |
| Mass fraction of hemicellulose (dry basis) % | 42.7±1.7 | 33.6±5.2 |

Table 2 presents the proximate analysis of lavender, according to the authors of [16].

Table 2. Proximate analysis of lavender according to [16].

| Biomass/component, wt % | VM | FC | M | A | Total |
|------------------------|----|----|---|---|-------|
| lavender               | 66.7 | 15.3 | 10.2 | 7.8 | 100   |

Table 3. Working composition of lavender stalks after the distillation process [14].

| Composition | N   | C   | Cl  | H   | O   | S   | Ash | Humidity, wb% | HHV, MJ/kg |
|-------------|-----|-----|-----|-----|-----|-----|-----|--------------|------------|
| Mass share (db%) | 1.3 | 48.1 | 0.2 | 5.8 | 37.8 | 0.1 | 6.7 | 61           | 19.570     |

For comparison, there are studies [17] in which the HHV and ash content after the process of burning straws of lavender, thyme, sage, fennel and thistle were evaluated experimentally. The HHV was determined as initially, the biomass was dried to 22% humidity, and then, using a laboratory dryer was dried to 4.5% humidity. The cited publication presents results according to which the HHV of lavender stalks is 20.66 MJ/kg.

A higher content of lignin compared to that of cellulose implies a higher yield of solid residue, a higher content of volatile substances implies a higher amount of biooil and synthetic gas. The contradiction of the expected results requires an experiment in the laboratory in order to find the relationship between the process parameters, the quantities of pyrolysis products obtained and their distribution by species.

An experiment was performed with lavender stalks, after steam distillation at a temperature in the pyrolysis reactor 350°C - 400°C. The obtained results are presented in table 4 and table 5, being compared with those of the analytical calculations.

Table 4 presents the results for product yields from the experiment and compares with the predicted values calculated from the described models in the literature – (1), (2), (3), (4), (5), (6), (7). No publications have been found in the literature on experimental studies of the process of pyrolysis of lavender stalks. For this reason, in table 4 compares the results of the experimental studies in this article with those of other authors, selecting biomass with a similar composition (cellulose, hemicellulose and lignin).
Table 5 presents the result of the gas analysis of the obtained pyrolysis gas.

| Autor          | Biomass            | Temperature, °C | Structural composition (wt. %) | Pyrolysis products | Char | Oil | Gas |
|----------------|--------------------|-----------------|--------------------------------|--------------------|------|-----|-----|
| This paper     | Lavender straw     | 350             | 38,2                           | Pred.              | 22,8 | 35  | 10  |
|                |                    |                 | 21,5                           | Exp.               | -    | -   |     |
|                |                    |                 | 40,3                           | Pred.              | 77,2 | 55  |     |
|                |                    |                 |                                | Exp.               | -    | -   |     |
| Demirbas [7]   | Tea waste          | 450             | 33,2                           | 27,9               | 72,1 |     |     |
|                |                    |                 | 23,3                           | 38                 |     |     |     |
|                |                    |                 | 43,5                           | -                  |     |     |     |
| Mohammed [2]   | Napier gras        | 450             | 38,75                          | 18,8               | 81,2 |     |     |
|                |                    |                 | 19,76                          | 46                 | 26   |     |     |
|                |                    |                 | 26,99                          | 28                 |     |     |     |

The results of the calculated values of the HHV of lavender stalks and pyrolysis products are shown in the table 3 and table 5, using the models in (9), (10), (11) and (12).

The main problem in compiling the energy balance of the pyrolysis process is the determination of the heat required for the realization of the gasification process. Different authors offer different approaches.

According to the author of [6], the calculation of the heat required to perform endothermic reactions in the pyrolysis process is 1,683 kWh/kg raw, which is comparable to the values obtained from the calculation by formulas in table 3 - 2,003 kWh/kg raw.

The analysis of the results in tables 1 to 5 shows that the heat obtained from the burning of 1 kg of waste lavender stalks is 5.436 kWh. The heat obtained from the combustion of pyrolysis products per 1 kg of lavender waste stalks is 9,996 kWh. From the point of view of ecology and environmental pollution, pyrolysis is a gentle technology for obtaining energy from the waste stalks of lavender, which has become increasingly important in recent years.

Table 6 compares the characteristics of the energy balance of the two biomass conversion processes from lavender stalks.

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| Component | H2 | CO | CO2 | H2S | CH4 | LHV, MJ/kg |
|-----------|----|----|-----|-----|-----|------------|
| vol %     | 1,9| 12,3| 21  | 790 ppm | 64,8 | 26,418     |

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| Process      | Income from incineration, kWh/kg raw | Costs, kWh/kg raw | Profit, kWh/kg raw | Ecological effect          |
|--------------|--------------------------------------|-------------------|--------------------|---------------------------|
| Direct combustion | 5,436                               | -                 | 5,436              | NOx, SO2, dioxins         |
| Pyrolysis    | 9,996                                | Pyrolysis 2,003   | 6,84               | No harmful substances are released |
burning of pyrolysis products does not pollute the environment, while the burning of lavender straws releases NOx, SO2 and dioxins.

The energy analysis concluded that the energy contained in the lavender waste stalks after the steam distillation process could be used, preferably by pyrolysis, which is an environmentally friendly technology. Extracting energy through pyrolysis from waste lavender stalks leads to economic and environmental benefits.

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