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EVALUATION OF WASTE BIOMASS FROM AROMATIC PLANTS FOR ENERGY PURPOSES

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Abstract

This study aims to evaluate the feasibility of obtaining energy from waste biomass. The potential of waste biomass from aromatic plants, left after the production of essential oils, was assessed. The calorific value, ash content, volatile compounds, and moisture content were determined. Elemental analysis of the waste biomass was conducted to measure the C, H, N, and S contents. The results indicate that residual waste has significant potential as a quality feedstock for solid biofuel production. Compared to coal, the calculated emission factors demonstrate a reduction in CO and CO2 emissions by up to 30%, NOx by up to 80%, SO2 by up to 99%, and dust by up to 67%, depending on the waste used. When selecting suitable waste for energy production, it's essential to balance calorific value and emission factors. If energy efficiency is the priority, lavender, tansy, and thyme waste may be preferred. However, for sustainability and lower environmental impact, common sage waste could be the better choice. It's important to consider the specific context, including regulations and energy needs, when making a final decision.

***Key words**: biofuel, elemental analysis, emission factors, waste.*

INTRODUCTION

In recent years, alternative energy sources characterized by low emissions, including greenhouse gases and dust particles, have been increasingly sought after (Kimming et al., 2015; Obernberger et al., 2017). Waste plays a crucial role in the European Commission's strategy for energy security and greenhouse gas (GHG) emission reduction. As a renewable energy source, the use of waste biomass has been expanding worldwide, primarily for household heating as an alternative to fossil fuels (Lasek et al., 2018; Pastorello et al., 2011). The demand for plants with high productivity, low nutrient requirements, and valuable biological composition for various bioeconomic applications is of utmost importance. Perennial plants, in particular, offer advantages by reducing production costs and energy inputs compared to annual field preparation and planting. Additionally, such a biomass production system can enhance ecosystem services and support soil conservation, aligning with the concept of "low energy consumption and high output" regarding energy investments and additional costs. Essential oil crops are primarily cultivated for their essential oils (Duce et al., 2017; Giacometti et al., 2018; Kant & Kumar, 2022). The area dedicated to essential oil production in the European Union is steadily increasing, reaching approximately 80,000 hectares (Maj et al., 2020). In recent years, global trade in medicinal and aromatic plants has grown by 10-12% annually (Chandra & Sharma, 2019). Consequently, waste generation in this industry has also increased, reaching up to 30 million tons annually (Wei et al., 2022).

A substantial amount of waste biomass is generated during harvesting, pre-processing, drying, collection of harvested crops, and plant feedstock processing. After essential oil extraction, solid residue remains, which can be utilized for fuel energy production through pyrolysis, gasification, or hydrothermal carbonization processes (Mastellone, 2015). Despite containing valuable substances, these residues are often discarded through stockpiling, landfilling, or open field burning, leading to resource waste and significant environmental pollution (Wei et al., 2022; Marcelino et al., 2023).

Despite the strong economic potential of utilizing plant biomass waste, limited research has focused on the calorific value of these residues (Maj et al., 2020; Chakyrova & Doseva, 2021; Pulidori et al., 2023).

This study aims to evaluate the energy potential of residues obtained after the steam distillation of essential oils from lavender, tansy, thyme, yarrow, and common sage. Additionally, it examines the emission factors of toxic exhaust components and explores the feasibility of using these residues for energy production.

MATERIALS AND METHODS

Aromatic plants, including lavender, tansy, thyme, yarrow, and common sage, were collected from southern Bulgaria at the flowering stage. After essential oil extraction via steam distillation, the plant residues were dried in an oven at 105°C and ground using a laboratory grinder. The physico-chemical characterization of the plant residues was conducted based on calorific value, ultimate analysis, and proximate analysis.

The heating value was determined following the ISO standard (BDS EN ISO 18125:2017) using an IKA C6000 oxygen bomb calorimeter (IKA Werke GmbH, Germany).

The samples were analyzed according to standard methods: moisture content (BDS EN ISO 18134-3:2015), ash content (BDS EN ISO 18122:2015), volatile matter (BDS EN ISO 18123:2015).

Total carbon, hydrogen, nitrogen, and sulfur contents were determined by dry combustion using a Vario Macro CHNS analyzer (Elementar GmbH, Germany) (BDS EN ISO 16948:2015).

Using the results from the ultimate analysis, emission factors for CO, CO_2, NO_x, SO_2, and dust emissions were estimated through equations (1)-(7) (Borycka, 2008):

CO emission factor

$$\mathrm{CO} = \frac{28}{12} x \ \mathrm{Ec} \ x \ (C\_CO/C) \quad (1)$$

Emission factor of chemically pure coal

$$Ec = c.uc \quad (2)$$

CO_2 emission factor

$$CO_2 = \frac{44}{12} x \ (Ec - \frac{12}{28} \ x \ CO - \frac{12}{16} \ x\mathrm{ECH}_4 - \frac{26.4}{31.4} x \ ENMVOC) \quad (3)$$

Methane emission factor:

$$ECH4 = \frac{16}{12} xEc \times \left(\frac{C_{CH4}}{C}\right) \quad (4)$$

NOx emission factor

$$NOx = \frac{46}{14} \times Ec \times \frac{N}{C} \times \left(\frac{N_{NOx}}{N}\right) \quad (5)$$

Emission factor of SO_2

$$\mathrm{SO_2} = \frac{2S}{100} \quad (6)$$

Dust emissions:

$$Edust = 1.5 \times A \times \frac{100 - \eta 0}{100 - k} \quad (7)$$

RESULTS AND DISCUSSIONS

Proximate and ultimate analysis

The proximate and ultimate analysis results for essential oil plant waste are presented in Tables 1 and 2. According to CEN/TS 14961, biomass for solid biofuels is categorized into three main groups: woody biomass, herbaceous biomass, and fruit biomass. Essential oil plant waste falls under the herbaceous biomass group - specifically, agricultural and garden herbs.

Table 1. Proximate analysis and heating values of plant waste

Plant waste	M, %	Ash, %	FC, %	VM, %	LHV, MJ/kg	HHV, MJ/kg
Lavender	8.42	7.28	11.5	80.08	17.41	19.23
Tansy	7.31	8.35	12.69	80.0	18.16	19.78
Thyme	7.08	8.24	14.42	78.5	17.85	19.17
Yarrow	6.22	8.79	16.48	77.3	16.7	17.96
Commom sage	8.95	6.22	13.46	77.59	16.24	18.06
ISO 17225-6	≤12 - 15	≤ 6-10	-	-	≥14.5	-
CEN/TS 14961-1Harvest (July - Oct.)	-	6.5 (2.5-10)	-	-	16.6	-

M - moisture, FC- fixed carbon, VM - volatile matter, LHV - lower heating value, HHV - higher heating value

The key parameters of biomass waste were compared against the requirements of the ISO 17225-6 standard for herbaceous biomass and data from other studies.

Heating Value and Energy Potential: The LHV (Lower Heating Value) is a crucial parameter for evaluating biomass as a biofuel. According to ISO 17225-6, the standard LHV for solid fuel is ≥14.5 MJ/kg. The LHV of the tested plant waste ranged from 16.24 MJ/kg (common sage) to 18.16 MJ/kg (tansy). The tested biomass meets or exceeds ISO 17225-6 standards for LHV (≥14.5 MJ/kg), indicating good energy potential.

The HHV (Higher Heating Value), which represents the total energy content, ranged from 17.96 MJ/kg (yarrow) to 19.78 MJ/kg (tansy). Tansy waste shows the highest energy efficiency (19.78 MJ/kg HHV), making it an excellent candidate for biofuel. Conversely, the lower HHV of common sage implies reduced energy potential. These values align with previous studies, such as Pulidori et al. (2023) for lavender waste (19.2 MJ/kg) and thyme waste (17.8 MJ/kg), Maj et al. (2020) for mint waste (15.90-16.64 MJ/kg), and Zając et al. (2019) for miscanthus (17.99 MJ/kg), wood (18.35 MJ/kg), and rapeseed straw (15.97 MJ/kg).

Moisture Content and Ash Content: Moisture content significantly affects combustion efficiency, as lower moisture levels lead to better energy performance. The tested biomass had moisture content ranging from 6.22% (yarrow waste) to 8.95% (common sage waste), which complies with ISO 17225-6 (≤12-15%).

Ash content is a critical parameter in biomass fuel quality, as higher ash levels can reduce combustion efficiency and cause operational challenges. The tested samples contained 6.22% (common sage) to 8.79% (yarrow) ash, which is within the acceptable ISO 17225-6 range (≤6-10%). Moisture and ash contents are within acceptable ranges, ensuring good combustion properties. These values are comparable to previous findings for lavender waste (6.7-7.8%) (Chakyrova & Doseva, 2021) andmint waste (7.23-10.29%) (Maj et al., 2020).

Fixed Carbon and Volatile Matter: Fixed carbon content is a positive attribute of biomass, as it determines combustion stability and burning duration. While ISO 17225-6 does not specify a standard for fixed carbon, the values in this study ranged from 11.5% (lavender) to 16.48% (yarrow), with yarrow showing the highest combustion stability. Similar values were reported for mint waste: 9.40-15.77% (Maj et al., 2020) andlavender waste: 15.3% (Chakyrova & Doseva, 2021).

Volatile matter plays a key role in biomass combustion, with higher volatile content leading to easier ignition and more intense burning. Fixed carbon and volatile matter values indicate stable burning characteristics. Biomass typically contains 60-80% volatile matter, and the tested biomass samples ranged from 77.3% (yarrow) to 80.08% (lavender). These values align with mint waste (64.99-70.36%) (Maj et al., 2020), miscanthus (72.5%) and rapeseed straw (73.5%) (Zając et al., 2019).

Table 2 presents the results of the ultimate analysis of the tested wastes. These values are compared with the requirements of ISO 17225-6 and with findings from other studies. The main components of solid biofuels are carbon (C), hydrogen (H), and oxygen (O). During combustion, C and H undergo oxidation in exothermic reactions, forming CO_2 and H_2O, which impact the gross calorific value of the fuel (Clarke & Preto, 2011). Higher C content indicates a greater energy potential for biomass, making it more viable as a renewable energy source. The total C content in the tested samples ranged from 46.9% to 49.3%, with lavender waste exhibiting the highest values. Similar C content has been reported for mint waste (44.82-47.05%) (Maj et al., 2020), lavender (45.4-48.1%) (Chakyrova & Doseva, 2021), willow biomass (50.84%) (Szczukowski et al., 2015), and wood (49.80%) (Kajda-Szczesniak, 2013). Hydrogen content ranged from 3.8% (tansy waste) to 5.53% (common sage waste). Comparable H content has been observed in mint waste (5.54-5.76%) (Maj et al., 2020), lavender waste (5.8-6.77%) (Chakyrova and Doseva, 2021), willow biomass (5.86%) (Szczukowski et al., 2015), and wood (6.30%) (Kajda-Szczesniak, 2013). These values are also close to those of wheat, barley, flax, and timothy straw (6.1-6.4%). Oxygen content negatively affects the energy value. The O content of the tested biomass ranged from 37.81% to 41.00%, with no significant differences among the samples. These values are similar to those of wheat, barley, flax, and timothy straw (44.4-52.1%) but lower than those reported for mint waste (29.14-36.09%) (Maj et al., 2020) and lavender waste (37.8%) (Chakyrova & Doseva, 2021). According to Vassilev et al. (2010), the elemental composition of biomass is a key factor in estimating heating values, combustion air requirements, and the composition of flue gases. Knowledge of elemental composition also helps assess gaseous emissions from fuel combustion. From an environmental perspective, N and S contribute to greenhouse gas emissions and are considered undesirable in biomass fuels. During combustion, N leads to NOx emissions, while S contributes to SOx emissions, which can cause particulate pollution, acid rain, and corrosion (Clarke & Preto, 2011). The N content in the tested biomass ranged from 0.178% (lavender waste) to 0.36% (tansy waste), remaining well below the 1.5-2% limit set by ISO 17225-6. Lower nitrogen levels improve the suitability of biomass for combustion. Comparable N values have been reported for mint waste (0.23-0.70%) (Maj et al., 2020) and lavender (1.3%) (Chakyrova & Doseva, 2021).

Sulfur content in biomass is generally low but still plays a role in emissions. The sulfur levels in the tested samples ranged from 0.0334% (lavender waste) to 0.0784% (yarrow waste), remaining well below the 0.2-0.3% standard limit. Comparable S content has been reported for lavender waste (0.1%) (Chakyrova & Doseva, 2021) and mint waste (0.0-0.19%) (Maj et al., 2020). Low S content minimizes the risk of releasing SO_2 during combustion, reducing environmental impact.

Table 2. Ultimate analysis of tested wastes

Waste	N, %	S, %	Cl, %	C, %	H, %	O, %
Lavender	0.178	0.0334	0.0220	49.3	5.40	37.81
Tansy	0.360	0.0738	0.0895	49.2	3.80	38.22
Thyme	0.240	0.0593	0.0358	48.5	3.80	39.16
Yarrow	0.250	0.0784	0.2121	46.9	4.60	39.38
Common sage	0.198	0.0500	0.0148	47.0	5.53	41.00
ISO 17225-6	1.5-2	0.2- 0.3	0.1-0.3	-	-	-
CEN/TS 14961-1 Harvest (July-Oct.)	1.3	0.1 (0.1-0.2)	0.5 (0.2-0.6)	46	5.7	40

Chlorine levels ranged from 0.0148% (common sage) to 0.2121% (yarrow), staying within the allowable limits for solid fuels. Lower chlorine content is beneficial as it reduces the potential for corrosion and harmful emissions.

Emission factors

Determining emission factors is essential for estimating the levels of pollutants emitted during fuel combustion. To determine these factors, it's crucial to understand the physicochemical characteristics of the waste being used. The emission factors for CO, CO_2, NOx, SO_2, and dust emissions from the plant waste studied are presented in Table 3, along with data for coal emissions for comparison.

Table 3. Emission factors (kg/mg) for analysed waste and coal

Waste	CO	CO_2	NOx	$S0_2$	Edust
Lavender	60.74	1487.07	0.63	0.067	9.20
Tansy	60.61	1484.05	1.27	0.148	10.55
Thyme	59.75	1462.94	0.85	0.119	10.41
Yarrow	57.78	1414.66	0.88	0.157	11.10
Common sage	57.90	1417.68	0.70	0.100	7.86
Hard coal	82.01	1969	4,09	5,2	23,57

No significant differences were observed in the carbon monoxide (CO) emission levels of the investigated plant wastes. The highest CO emission rate was observed for lavender (60.74 kg/mg), while the lowest was for yarrow (57.78 kg/mg), with a difference of up to 3%.

The Nox emissions ranged from 0.6289 kg/mg for lavender waste to 1.27 kg/mg for tansy waste.

The CO_2 emission factor was highest for tansy waste (1484.05 kg/mg) and lowest for yarrow waste (1414.66 kg/mg).

SO_2 emissions ranged from 0.067 kg/mg for lavender waste to 0.118 kg/mg for thyme waste. Dust emissions were highest for yarrow waste (11.10 kg/mg) and lowest for common sage (7.86 kg/mg).

The emission factors show that the tested wastes exhibit similar emission levels to those of mint waste (Maj et al., 2020), Eucalyptus globulus tree (Mateos et al., 2019), and larch needles (Maj, 2018). Overall, emissions are comparable to other waste types, and the SO_2 content in the wastes is minimal. CO and CO_2 emission factors are similar to those for mint (Maj et al., 2020), larch needles (Maj, 2018), and hazelnut husk and leaves (Maj, 2018; Borkowska et al., 2024).

Plant wastes have significantly lower NOx emissions compared to straw pellets, sunflower stalks, corn stalks, and wood pellets (Krugly et al., 2014), as well as Eucalyptus globulus (Mateos et al., 2019).

Wastes from lavender, thyme, and yarrow showed higher particulate emissions similar to those from mint waste (9.14-13.0%) (Maj et al., 2022), tree leaves (10.80%) (Maj, 2018), and hazelnut waste (10.95%) (Borkowska et al., 2024). The high dust emissions are associated with the high ash content of the tested wastes, so technological solutions to reduce these emissions (e.g., using additional filters to capture emitted dust) should be considered.

The emission method for determining gas and dust emissions allows for an assessment of the environmental impact of plant waste when used for energy purposes, without requiring specialized analytical equipment. This method enables quick estimation of biofuel emissivity, which is often overlooked when assessing biomass suitability for energy.

Differences in emissions among the tested wastes may influence selection decisions, especially when considering environmental aspects and incineration efficiency. Based on the emission factors, common sage waste is characterized by low emissions. Higher emission factors for CO and CO_2 were found for lavender and tansy waste. Using common sage waste as a source of energy can contribute to reduction in GHG emissions.

Using waste from essential oil crops results in emission reductions compared to coal (Borycka et al., 2008). Emission levels decreased by 26-30% for CO, 24-28% for CO_2, 68-84% for NOx, 97-99% for SO_2, and 53-67% for dust, depending on the type of waste used. Therefore, utilizing these wastes as fuel provides real environmental benefits.

CONCLUSIONS

Significant differences were found between the plant wastes in terms of calorific value. Lavender waste (17.40 MJ/kg; 19.23 MJ/kg), tansy waste (18.16 MJ/kg; 19.78 MJ/kg), and thymewate (17.85 MJ/kg; 19.17 MJ/kg) showed higher lower and higher heating values, making them an excellent candidate for biofuel compared to yarrow waste (16.7 MJ/kg; 17.96 MJ/kg) and common sage (16.24 MJ/kg; 18.06 MJ/ kg).

The chemical composition of plant wastes affects their energy value and emission factors. The common sage waste is characterised by a higher moisture content (8.95%), which negatively affects the energy value of the waste.

The type of waste mainly influences the amount of emissions from waste incineration. Higher emissions of CO (60.61 and 60.76 kg/mg) and CO_2 (1484.05-1487.07 kg/mg) were found for tansy and lavender waste, NOx - for tansy waste (1.26 kg/mg), while for yarrow there are higher dust emissions (11.10 kg/mg).

When selecting suitable waste for energy production, it's essential to balance calorific value and emission factors. If energy efficiency is the priority, lavender, tansy, and thyme waste may be preferred. However, for sustainability and lower environmental impact, common sage waste could be the better choice. It's important to consider the specific context, including regulations and energy needs, when making a final decision.

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