



Techno-Environmental Assessment of Basil Essential Oil Extraction Using Hydrodistillation, Microwave-Assisted Extraction, and Ultrasound-Microwave-Assisted Extraction

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ABSTRACT

This study evaluated the techno-environmental performance of basil (*Ocimum basilicum* L.) essential oil extraction using hydrodistillation (HD), microwave-assisted extraction (MAE), and ultrasound-microwave-assisted extraction (UMAE). The assessment focused on electricity consumption, specific electricity consumption, CO₂ emission, and specific CO₂ emission, while yield and essential oil mass were used as supporting parameters for normalization. UMAE produced the highest essential oil mass of 0.747 g with a yield of 2.489%, followed by MAE at 0.234 g and 0.780%, and HD at 0.206 g and 0.687%. UMAE also required the lowest electricity consumption of 0.345 kWh, compared with 0.450 kWh for MAE and 2.000 kWh for HD. On a product-mass basis, UMAE showed the lowest specific electricity consumption and specific CO₂ emission, reaching 0.462 kWh/g EO and 0.370 kg CO₂/g EO, respectively. These results indicate that ultrasound pretreatment followed by microwave extraction can improve energy efficiency and reduce electricity-related CO₂ emission intensity in basil essential oil extraction.

Keywords: basil essential oil, CO₂ emission, microwave-assisted extraction, specific electricity consumption, ultrasound-microwave-assisted extraction.

1. INTRODUCTION

Basil (*Ocimum basilicum* L.) is an aromatic plant widely used as a source of essential oil for food, pharmaceutical, cosmetic, perfumery, and aromatherapy applications. Its essential oil value is related to volatile compounds that contribute to aroma, flavor, and biological activities. The yield and composition of basil essential oil are influenced by raw material and processing conditions, including plant part, seasonal variation, and extraction method. Previous studies reported that basil essential oil content varied from 0.5% to 0.8% under different seasonal conditions, while different plant parts also produced different oil yields and chemical profiles [1,2].

The growing demand for natural essential oils has encouraged the development of

extraction methods that are more efficient and environmentally favorable. In green extraction, process performance is assessed not only from yield, but also from energy requirement, extraction time, solvent use, and environmental impact [3]. Hydrodistillation (HD) is commonly used for essential oil extraction because it is simple, solvent-free, and suitable for laboratory-scale volatile oil isolation using a Clevenger-type apparatus [4,5]. However, HD generally requires continuous heating and longer extraction time, which may increase electricity consumption and indirect CO₂ emission. Microwave-based extraction has been reported to reduce extraction time and energy demand compared with conventional distillation [6,7].

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Microwave-assisted extraction (MAE) offers rapid and volumetric heating through the interaction between microwave energy and polar molecules in the plant matrix. This mechanism can accelerate cell rupture and the release of volatile compounds. Cardoso-Ugarte et al. [8] reported that MAE of essential oils from herbs, including basil, could reduce extraction time, energy consumption, cost, and CO₂ emission. Tran et al. [6] optimized microwave-assisted hydrodistillation of basil and obtained an actual yield of 0.6% at a water-to-material ratio of 3.2:1, extraction time of 97 min, and microwave power of 430 W. Kusuma et al. [9] further reported that, for fresh basil leaves, hydrodistillation consumed approximately 1 kWh more electricity and generated 0.80 kg more CO₂ than solvent-free microwave extraction.

These differences show that improving essential oil extraction involves more than increasing oil yield. The energy required to obtain the product is also important, particularly when heating represents a major part of the process energy demand. A broader review of essential oil extraction technologies reported that microwave-assisted hydrodistillation increased oil yield by about 32% while reducing extraction time by an average of 67.17% compared with conventional hydrodistillation [10]. Thus, changes in extraction method can affect product recovery and energy demand simultaneously. A method with a higher yield may still require substantial energy, while a method with low total electricity consumption may appear efficient simply because it produces less oil. Electricity consumption is also relevant from an industrial perspective because it contributes to utility costs and, depending on the electricity source, to indirect CO₂ emissions. Energy use and emissions therefore need to be considered together with oil recovery when comparing extraction methods.

Ultrasound-assisted extraction is also used as an intensification technique because acoustic cavitation can disrupt plant cell structures, enhance mass transfer, and facilitate the

release of intracellular compounds [11]. The combination of ultrasound and microwave treatment in ultrasound-microwave-assisted extraction (UMAE) may provide a synergistic effect because different extraction mechanisms can complement each other [12]. Abbasi et al. [13] reported that sequential ultrasound-microwave extraction of *Ocimum basilicum* produced a yield of 2.3% w/w, higher than microwave extraction alone, which produced 0.74% w/w. A previous study on basil leaf UMAE also showed that ultrasonic temperature and pretreatment time significantly affected yield and physicochemical characteristics, with the best condition obtained at 50°C for 30 min reported that sequential ultrasound-microwave extraction of *Ocimum basilicum* produced a yield of 2.3% w/w, higher than microwave extraction alone, which produced 0.74% w/w. A previous study on basil leaf UMAE also showed that ultrasonic temperature and pretreatment time significantly affected yield and physicochemical characteristics, with the best condition obtained at 50°C for 30 min [14].

Although previous studies have provided important information on basil essential oil extraction, most have focused on yield, extraction time, chemical composition, physicochemical properties, or biological activity. Electricity consumption and CO₂ emission have been evaluated for HD and microwave-based methods such as SFME [9], whereas previous work on basil UMAE has mainly addressed yield and oil quality. It therefore remains unclear whether the additional ultrasound pretreatment in UMAE increases the overall energy burden or whether the higher oil recovery compensates for the electricity required for this additional step. A direct comparison of HD, MAE, and UMAE on the same product basis is therefore needed.

To address this issue, electricity consumption and CO₂ emission were normalized to the mass of essential oil produced. Specific electricity consumption represents the electricity required to produce 1 g of essential

oil, while specific CO₂ emission represents the corresponding electricity-related CO₂ emission per gram of oil. Meziane et al. [15] evaluated extraction energy efficiency based on energy consumed per unit mass of essential oil, while Moura et al. [16] used product-based functional units to compare energy use and carbon emissions in essential oil extraction. Accordingly, this study compares the techno-environmental performance of HD, MAE, and UMAE based on electricity consumption, specific electricity consumption, CO₂ emission, and specific CO₂ emission. Yield and essential oil mass are used as supporting parameters for product normalization. The comparison is intended to determine whether the higher oil recovery obtained by UMAE is accompanied by lower energy use and electricity-related CO₂ emission per gram of essential oil produced.

2. RESEARCH METHODS

2.1. Materials Preparation

Fresh basil leaves (*Ocimum basilicum* L.) were used as the raw material for essential oil extraction. The basil leaves were obtained from the agricultural area of Kelompok Tani Kosagraha Lestari, Surabaya, Indonesia. Distilled water was used as the extraction medium. Before extraction, the basil leaves were cut into approximately 1 cm pieces and dried in an oven at 70°C for 50 min. The drying temperature was selected considering previous studies on the drying characteristics of *Ocimum* leaves [17], while the drying duration was determined from a preliminary trial. During drying, the samples were monitored and turned every 10 min to promote uniform drying.

The extraction was carried out using 30 g of dried basil leaves and 300 mL of distilled water, corresponding to a feed-to-solvent ratio of 1:10 (w/v). The raw material preparation followed the previous UMAE experimental work on basil leaf essential oil extraction [14].

2.2. Hydrodistillation

HD was used as the conventional extraction method for comparison with microwave-based methods. HD is commonly applied for essential oil extraction because of its simple operation, solvent-free process, and suitability for laboratory-scale volatile oil isolation [4,5]. The schematic diagram of the HD apparatus that adopted and redrawn from the setup reported by Samadi et al. [18] is shown in Figure 1. In this method, 30 g of dried basil leaves and 300 mL of distilled water were placed in the distillation flask, corresponding to a feed-to-solvent ratio of 1:10 (w/v). The mixture was heated for 60 min to evaporate volatile compounds from the basil leaves. The vapor mixture was then condensed, and the essential oil was separated from the aqueous phase. The vapor mixture was then condensed, and the essential oil was separated from the aqueous phase.

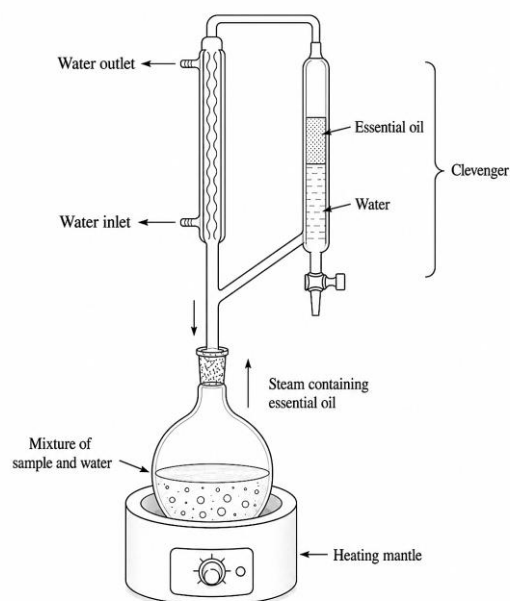


Figure 1. Schematic diagram of the hydrodistillation apparatus used for basil essential oil extraction.

The obtained essential oil was collected and weighed to determine extraction yield and techno-environmental parameters. HD was included as the baseline method because conventional distillation generally requires longer heating time and higher energy input than microwave-based extraction methods

[7,9]. For the energy calculation, the HD process was evaluated based on a heating power of 2.0 kW and an extraction time of 60 min.

2.3. Microwave-Assisted Extraction

MAE was conducted using dried basil leaves and distilled water at the same feed-to-solvent ratio of 1:10 (w/v). The extraction was performed using an Electrolux microwave system (Model EMM 2380 X) operating at a frequency of 2450 MHz. The microwave power was set at 450 W for 60 min. The schematic diagram of the MAE apparatus is shown in Figure 2(b). During the process, microwave energy generated rapid internal heating through the interaction between electromagnetic waves and polar molecules in the extraction medium. This mechanism can accelerate the release of volatile compounds and shorten extraction time compared with conventional heating [6,8].

The essential oil released from the plant matrix was carried by vapor, condensed, and separated from the aqueous phase. The collected essential oil was then weighed and used for techno-environmental analysis. MAE was included because previous studies have shown that microwave-based extraction can improve basil essential oil recovery while reducing electricity consumption and CO₂ emission compared with HD [8,9].

2.4. Ultrasound-Microwave-Assisted Extraction

UMAE was carried out in two sequential stages: ultrasound pretreatment followed by microwave extraction. In the first stage, dried basil leaves and distilled water were placed in a closed extraction vessel and treated using a 10 L ultrasonic cleaning bath (Model 410HTD) operating at a frequency of 40 kHz and an ultrasonic power of 240 W. The experimental variation used ultrasound temperatures of 30, 40, 50, 60, and 70°C and ultrasound times of 5, 15, 30, 45, and 60 min. Ultrasound pretreatment was applied because acoustic cavitation can disrupt plant cell structures, improve mass transfer, and

facilitate the release of intracellular compounds [11].

The UMAE condition evaluated in this study was selected from previous optimization work, in which ultrasound pretreatment at 50°C for 30 min followed by microwave extraction at 450 W for 30 min produced the highest basil essential oil yield [14].

For the energy calculation, the electricity consumption of UMAE included ultrasound pretreatment and microwave extraction. The ultrasonic bath power was 240 W, while the microwave power was 450 W.

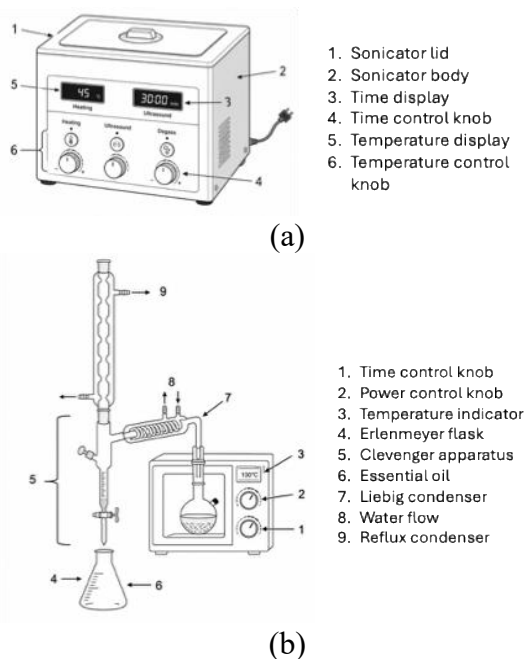


Figure 2. Schematic diagram of the extraction apparatus: (a) ultrasonic cleaning bath used for ultrasound pretreatment and (b) microwave-assisted extraction system equipped with a Clevenger-type separator and condenser.

The experimental apparatus used for ultrasound pretreatment and microwave extraction is illustrated in Figure 2. The apparatus scheme was redrawn and modified based on the extraction setup reported by Wicaksono et al. [19]. The ultrasonic cleaning bath was used to provide acoustic cavitation during the pretreatment stage, while the microwave extraction system was connected to a Clevenger-type separation unit and condenser to recover basil essential

oil. In the MAE method, only the microwave extraction system was used, whereas in the UMAE method, the microwave extraction stage was preceded by ultrasound pretreatment.

The selected UMAE condition was then used as the basis for comparison with MAE and HD. The use of sequential ultrasound-microwave treatment is supported by previous work on *Ocimum basilicum*, in which the combined method produced a higher essential oil yield than microwave extraction alone [13].

The extraction yield for each method (HD, MAE, and UMAE) was determined in triplicate ($n = 3$) to account for experimental variability.

2.5. Techno-Environmental Assessment

In this study, techno-environmental assessment refers to a process-level comparison that combines technical extraction performance with electricity-related environmental indicators. The technical assessment includes essential oil yield, product mass, operating power and time, electricity consumption, and specific electricity consumption, while the environmental assessment is represented by indirect CO₂ emission and specific CO₂ emission associated with electricity use. This approach is intended as a comparative screening of the extraction stage rather than a full life cycle assessment or techno-economic analysis.

The essential oil yield was calculated using Equation (1):

$$Y = \frac{m_{EO}}{m_b} \times 100 \quad (1)$$

where Y is the essential oil yield (%), m_{EO} is the mass of essential oil obtained (g), and m_b is the mass of dried basil leaves used as raw material (g).

Electricity consumption was estimated from the rated power of the equipment and the corresponding operating time rather than measured directly using a power meter. Therefore, the reported electricity

consumption represents theoretical electricity demand based on equipment specifications and operating duration. The calculation was based on Equation (2), following previous studies on energy assessment in essential oil extraction [9,15]. This calculation assumes that the equipment operates at its nominal power throughout the extraction process. Although actual power consumption may fluctuate during operation, the same assumption was applied consistently to all extraction methods to ensure a fair comparison.

$$EC = P \times t \quad (2)$$

where EC is electricity consumption (kWh), P is equipment power (kW), and t is operating time (h). When power is expressed in watts and time is expressed in seconds, the calculation can be written as Equation (3):

$$EC = \frac{P \times t}{3600000} \quad (3)$$

where P is equipment power (W), and t is operating time (s).

Specific electricity consumption was calculated to determine the electricity required to produce one gram of basil essential oil. This parameter was used because energy assessment based on energy consumed per mass unit of essential oil provides a more representative comparison among extraction methods [15]. The specific electricity consumption was calculated using Equation (4):

$$SEC = \frac{EC}{m_{EO}} \quad (4)$$

where SEC is specific electricity consumption (kWh/g EO), EC is electricity consumption (kWh), and m_{EO} is the mass of essential oil obtained (g).

An electricity emission factor of 0.8 kg CO₂/kWh was used to estimate indirect CO₂ emissions. This value corresponds to the 2017 baseline operating-margin emission factor reported for the Jawa–Madura–Bali (JAMALI) electricity system by the

Indonesian government [20]. The same factor was also used by Kusuma et al. [9] in estimating electricity-related CO₂ emissions from basil essential oil extraction. CO₂ emission was calculated using Equation (5):

$$E_{CO_2} = EC \times EF \quad (5)$$

where E_{CO_2} is CO₂ emission (kg CO₂), EC is electricity consumption (kWh), and EF is the electricity emission factor (kg CO₂/kWh).

Specific CO₂ emission was calculated to evaluate the emission intensity of each extraction method. This parameter represents the amount of CO₂ emitted per gram of basil essential oil produced. The use of a product-mass basis is relevant because previous environmental assessments of essential oil extraction have used functional units based on 1 g of aromatic extract to compare energy and carbon emission performance [16]. Specific CO₂ emission was calculated using Equation (6):

$$SE_{CO_2} = \frac{E_{CO_2}}{m_{EO}} \quad (6)$$

where SE_{CO_2} is specific CO₂ emission (kg CO₂/g EO), E_{CO_2} is total CO₂ emission (kg CO₂), and m_{EO} is the mass of essential oil obtained (g).

For UMAE, electricity consumption was calculated from the total energy used during ultrasound pretreatment and microwave extraction. For MAE, electricity consumption was calculated from microwave power and extraction time. For HD, electricity consumption was calculated from heating power and distillation time. The techno-environmental performance of the three methods was then compared based on yield, essential oil mass, electricity consumption, specific electricity consumption, CO₂ emission, and specific CO₂ emission.

3. RESULTS AND DISCUSSION

The techno-environmental performance of basil essential oil extraction using HD, MAE,

and UMAE is presented in Table 1. The comparison was evaluated based on yield, essential oil mass, electricity consumption, specific electricity consumption, CO₂ emission, and specific CO₂ emission. In this study, yield and essential oil mass were included as supporting parameters because both values determine the basis for energy and emission normalization. Therefore, the discussion does not position yield as the main novelty, but uses it to explain the electricity and CO₂ emission intensity of each extraction method.

As shown in Table 1, UMAE produced the highest essential oil mass, reaching 0.747 g, followed by MAE at 0.234 g and HD at 0.206 g. The corresponding yields were 2.489%, 0.780%, and 0.687%, respectively. The higher yield obtained by UMAE is important in this assessment because it affects the specific electricity consumption and specific CO₂ emission values. However, the optimization of UMAE yield and physicochemical characteristics of basil essential oil has been reported in previous work [14]. For this reason, the present study uses yield and essential oil mass mainly as normalization parameters in the techno-environmental comparison.

The higher essential oil mass obtained by UMAE indicates that ultrasound pretreatment before microwave extraction improved the release of volatile compounds from basil leaves. Ultrasound pretreatment can generate acoustic cavitation, which disrupts plant cell structures, enhances solvent penetration, and improves mass transfer [11]. When the pretreated plant matrix is subsequently exposed to microwave heating, volatile compounds may be released more efficiently because the plant tissue has already been partially disrupted. This mechanism supports the idea that combined emerging extraction technologies can improve extraction performance because different physical mechanisms may complement each other during the release of target compounds [12].

Table 1. Techno-environmental performance of basil essential oil extraction using different methods.

Method	Yield (%)	Essential oil mass (g)	Electricity consumption (kWh)	Specific electricity consumption (kWh/g EO)	CO ₂ emission (kg CO ₂)	Specific CO ₂ emission (kg CO ₂ /g EO)
HD	0.687 ^a	0.206	2.000	7.793	1.600	6.234
MAE	0.780 ^b	0.234	0.450	1.557	0.360	1.245
UMAE	2.489 ^c	0.747	0.345	0.462	0.276	0.370

Yield values were obtained from triplicate measurements (n = 3). ^a)standard deviation (SD) = 0.0456; ^b)SD = 0.0173; ^c)SD = 0.0184.

The positive role of pretreatment has also been reported in other essential oil extraction systems. Yu et al. [21] reported that ultrasound and microwave pretreatments improved hydrodistillation extraction of essential oils from kumquat peel by affecting extraction kinetics and oil recovery. Chen et al. [22] also showed that ultrasound pretreatment combined with microwave-assisted hydrodistillation improved the extraction of essential oil from *Perilla frutescens* leaves. These findings support the interpretation that pretreatment can increase the accessibility of oil-containing structures before the main extraction stage. In the present study, this effect was reflected in the higher essential oil mass obtained using UMAE compared with MAE and HD.

From the energy perspective, HD showed the highest electricity consumption, reaching 2.000 kWh. This value was much higher than MAE and UMAE, which consumed 0.450 kWh and 0.345 kWh, respectively. The high electricity consumption of HD is associated with the continuous heating requirement during the distillation process. In HD, heat must be transferred from the heating source to water and then to the plant matrix before volatile compounds can evaporate and be condensed. This indirect heating pathway generally requires a longer heating period and higher energy input. In contrast, microwave-based extraction provides more direct and volumetric heating through the interaction between microwave energy and polar molecules in the extraction medium [8].

This explains why MAE and UMAE required lower total electricity consumption than HD. Although UMAE included an additional ultrasound pretreatment stage, its total electricity consumption remained lower than MAE. This occurred because UMAE used ultrasound pretreatment for 30 min and microwave extraction for 30 min, whereas MAE used microwave extraction for 60 min. Based on Table 1, UMAE reduced total electricity consumption by 82.75% compared with HD and by 23.33% compared with MAE. This result indicates that the additional ultrasound stage did not increase the total energy burden. Instead, it contributed to a more efficient extraction process by improving the effectiveness of the subsequent microwave extraction stage.

However, total electricity consumption alone does not fully represent extraction efficiency because each method produced a different amount of essential oil. For this reason, specific electricity consumption was used to compare the electricity required to produce one gram of basil essential oil. Energy assessment based on energy consumed per mass unit of essential oil has been recommended as a more representative indicator for evaluating essential oil extraction processes [15]. The comparison of specific electricity consumption among HD, MAE, and UMAE is visualized in Figure 3. HD showed the highest specific electricity consumption, reaching 7.793 kWh/g EO. This means that HD required 7.793 kWh of electricity to produce one gram of basil essential oil. MAE showed a lower value of

1.557 kWh/g EO, indicating better energy performance than HD. UMAE showed the lowest specific electricity consumption, only 0.462 kWh/g EO. Compared with HD, UMAE reduced specific electricity consumption by 94.07%. Compared with MAE, the reduction reached 70.33%.

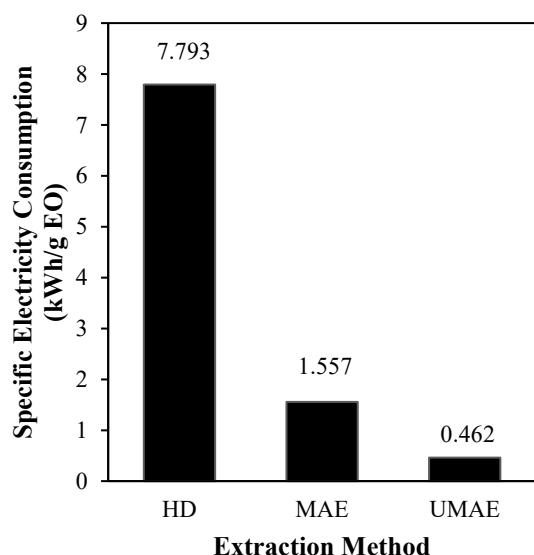


Figure 3. Specific electricity consumption of basil essential oil extraction using different methods.

The reduction in specific electricity consumption was more substantial than the reduction in total electricity consumption because UMAE not only consumed less electricity, but also produced a much higher mass of essential oil. This shows that the advantage of UMAE becomes clearer when energy input is normalized to product mass. In other words, UMAE did not merely reduce electricity use; it also improved the amount of essential oil obtained from the same raw material basis. This result is consistent with broader findings on microwave- and ultrasound-assisted essential oil extraction, which have reported improvements in extraction time, energy use, and process efficiency compared with conventional extraction methods [23].

The low specific electricity consumption of UMAE can be explained by the sequential contribution of ultrasound pretreatment and microwave extraction. Cavitation generated

during ultrasound pretreatment can damage plant cell walls, reduce mass transfer resistance, and increase the accessibility of essential oil-containing structures [11]. After this pretreatment, microwave heating can release volatile compounds more efficiently because the plant matrix has become more accessible to heat and mass transfer. This mechanism explains why UMAE produced higher essential oil mass with lower electricity consumption per gram of product. In contrast, HD showed the highest specific electricity consumption because it combined high total electricity consumption with relatively low essential oil recovery. MAE improved energy performance compared with HD, but its essential oil mass remained much lower than UMAE. Therefore, although MAE consumed less total electricity than HD, it was still less efficient than UMAE when evaluated on a product-mass basis. This confirms that specific electricity consumption is more informative than total electricity consumption for comparing extraction methods with different oil recovery levels.

Since CO₂ emission was estimated from electricity use, the total CO₂ emission followed the same trend as electricity consumption. The emission calculation used an electricity emission factor of 0.8 kg CO₂/kWh, following the approach used in previous basil essential oil extraction research [9]. HD produced the highest total CO₂ emission, reaching 1.600 kg CO₂. MAE produced 0.360 kg CO₂, while UMAE produced the lowest total CO₂ emission, 0.276 kg CO₂. Compared with HD, UMAE reduced total CO₂ emission by 82.75%. Compared with MAE, the reduction was 23.33%.

The lower CO₂ emission of MAE and UMAE compared with HD indicates that microwave-based extraction can reduce electricity-related environmental burden. Nevertheless, total CO₂ emission should be interpreted together with yield and energy intensity. Microwave-based extraction should not automatically be considered environmentally superior only because it can shorten

extraction time. Božović et al. [24] showed that environmental performance in essential oil extraction can vary depending on extraction power, operating conditions, yield, and process kinetics. Therefore, the comparison of HD, MAE, and UMAE should consider not only the total electricity consumed, but also the amount of essential oil produced.

Specific CO₂ emission was used to evaluate emission intensity per gram of basil essential oil. This indicator is important because it normalizes CO₂ emission to product mass, allowing a more balanced comparison among extraction methods with different yields. The use of product-based functional units has also been applied in environmental assessment of essential oil extraction because it allows energy and carbon emission performance to be compared based on the amount of product obtained [15]. The comparison of specific CO₂ emission among the three extraction methods is shown in Figure 4.

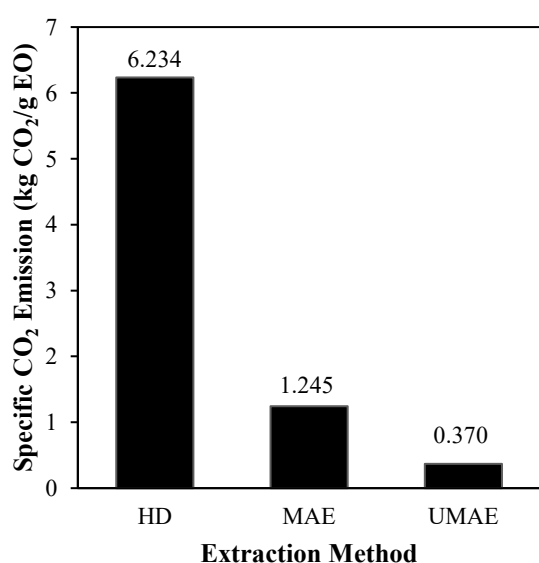


Figure 4. Specific CO₂ emission of basil essential oil extraction using different methods.

HD showed the highest specific CO₂ emission, reaching 6.234 kg CO₂/g EO. This indicates that producing one gram of basil essential oil using HD generated an estimated 6.234 kg CO₂ from electricity use. MAE reduced the value to 1.245 kg CO₂/g EO.

UMAE showed the lowest value, only 0.370 kg CO₂/g EO. Compared with HD, UMAE reduced specific CO₂ emission by 94.06%. Compared with MAE, the reduction reached 70.28%.

The reduction pattern of specific CO₂ emission was similar to that of specific electricity consumption because CO₂ emission was calculated directly from electricity consumption. Therefore, lower specific electricity consumption directly resulted in lower specific CO₂ emission. This relationship supports the use of product-normalized indicators in cleaner engineering assessment. Kusuma et al. [9] used specific energy consumption and CO₂ emission per gram of oil to evaluate the cleaner performance of microwave-based essential oil extraction, showing that product-normalized indicators are useful for comparing process performance more fairly. The comparison between MAE and UMAE further illustrates the importance of using specific indicators. Compared with MAE, UMAE reduced total CO₂ emission by 23.33%, while specific CO₂ emission decreased by 70.28%. At the same time, the essential oil yield increased from 0.780% for MAE to 2.489% for UMAE, corresponding to an increase of 219.10%. The greater reduction in specific CO₂ emission therefore reflects the combination of lower electricity-related CO₂ emission and higher essential oil recovery. This indicates that the environmental advantage of UMAE becomes more evident when emissions are evaluated on a product-mass basis rather than from total emissions alone.

Overall, UMAE showed the most favorable techno-environmental performance among the three extraction methods. HD had the highest electricity consumption and CO₂ emission because of its continuous heating requirement. It also produced the lowest essential oil mass, resulting in the highest specific electricity consumption and specific CO₂ emission. MAE improved energy and emission performance compared with HD, which is consistent with previous findings that microwave-based extraction can reduce

extraction time and electricity-related CO₂ emission compared with conventional extraction methods [8,9]. However, MAE still showed higher energy and emission intensity than UMAE because its oil recovery was lower.

The better performance of UMAE can be attributed to the combination of ultrasound pretreatment and microwave extraction. Ultrasound pretreatment enhanced plant matrix disruption through acoustic cavitation, while microwave heating accelerated volatile compound release through rapid internal heating [10–12,17,18]. This combination resulted in higher essential oil mass and lower electricity and CO₂ emission intensity. From the perspective of green extraction, this result supports the need to evaluate extraction methods not only from yield, but also from energy use and environmental impact [3].

The findings also show that normalized indicators are essential in techno-environmental comparison. If the assessment were based only on total electricity consumption and total CO₂ emission, the difference between MAE and UMAE would appear relatively small. However, when the values were normalized to essential oil mass, UMAE showed a much stronger advantage. This confirms that specific electricity consumption and specific CO₂ emission provide a more representative comparison for extraction methods with different oil recovery levels [14,15,21].

It should be noted that the CO₂ emission in this study represents indirect emission from electricity consumption only. In addition, electricity consumption was estimated from the nominal power rating and operating time rather than directly measured. Actual electricity use may vary during operation; therefore, the reported energy and CO₂ emission values should be interpreted as theoretical estimates under the stated operating conditions. Other environmental aspects, such as water use, equipment manufacturing, waste treatment, and raw material transportation, were not included. Therefore, this study should be understood as a techno-environmental assessment based on

estimated electricity consumption and electricity-related CO₂ emission, not as a full life cycle assessment. Nevertheless, applying the same calculation basis to all three methods provides a consistent basis for comparing their relative energy and emission intensities.

4. CONCLUSION

This study demonstrates that UMAE provides a more favorable techno-environmental performance than HD and MAE for basil essential oil production. The improvement was not only related to oil recovery, but also to the ability of the process to use electricity more efficiently and generate lower electricity-related CO₂ emission per unit of essential oil. The combination of ultrasound pretreatment and microwave extraction enhanced the extraction process by improving mass transfer before microwave heating, resulting in better energy and emission intensity. These findings indicate that product-normalized indicators, such as specific electricity consumption and specific CO₂ emission, are important for evaluating extraction methods more fairly than total energy or total emission alone. Since this study was limited to electricity use and indirect CO₂ emission, future research should consider scale-up evaluation and broader environmental aspects, including water use, material inputs, waste generation, and full life cycle impacts.

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AUTHOR CONTRIBUTIONS

A.N.A.F.: data analysis, visualization, interpretation, writing of the original draft, project administration. **A.A.N.A.:** experimental work, data acquisition, laboratory analysis. **M.T.Q.:** experimental work, data acquisition, laboratory analysis. **N.I.:** investigation, interpretation,

manuscript revision. **N.K.E.:** conceptualization, methodology, supervision, writing of the original draft.

CONFLICTS OF INTEREST

The authors declare no competing financial interests.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES

The authors used the generative technologies, OpenAI's ChatGPT, in order to improve readability and language of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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