

Research Article

Ohmic heating-assisted extraction of phenolic-rich extracts from lemongrass (*Cymbopogon citratus*) leaves: Process optimization, antioxidant activity, and LC–MS characterization

Fatemeh Goli , Fatemeh Ghiasi , Marzieh Moosavi-nasab , Mehrdad Niakousari* 

Department of Food Science and Technology, School of Agriculture, Shiraz University, Shiraz, I. R. Iran

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ABSTRACT- Lemongrass (LG, *Cymbopogon citratus*) leaves are recognized for their essential oil content, characteristic citrus-like aroma, and diverse biological activities, including anti-inflammatory and anticancer properties. In this study, ohmic heating-assisted extraction (OHE) was investigated as a novel approach for the recovery of bioactive compounds from LG leaves. The effects of extraction parameters, namely ethanol concentration (50% and 70%, v/v), extraction temperature (50 and 70 °C), and LG-to-solvent ratio (1:10, 1:15, and 1:20, w/v), were evaluated based on total phenolic content (TPC) and extraction yield (dry matter content). The performance of OHE was subsequently compared with conventional extraction techniques, including room-temperature maceration (ME) and magnetic stirrer-assisted extraction at elevated temperature (MSE). The results demonstrated that OHE under optimized conditions (50% ethanol, 50 °C, and a 1:10 LG-to-solvent ratio) produced the highest TPC (85.83 ± 2.28 mg GAE/g dry matter) and maximum antioxidant activity (44.95%). In contrast, the highest total flavonoid content (TFC) (19.06 ± 0.03 mg quercetin equivalents/g dry matter) was achieved using the MSE method. Liquid chromatography–mass spectrometry (LC–MS) analysis of the optimized ohmic-assisted hydroethanolic extract, performed in negative ionization mode, revealed the presence of several bioactive phytochemicals, including chlorogenic acid, caffeic acid, kaempferol derivatives, and apigenin derivatives. Overall, the findings indicated that OHE is an efficient and promising extraction technique for the recovery of phenolic compounds from lemongrass leaves. To the best of our knowledge, this is the first study that optimized ohmic heating extraction parameters specifically for enhancing phenolic compound extraction from *Cymbopogon citratus* leaves.

INTRODUCTION

In recent years, medicinal herbs have attracted considerable interest owing to their diverse functional properties and broad applications in the food, cosmetic, and pharmaceutical industries. Among these, lemongrass (*Cymbopogon citratus*), a perennial aromatic herb, is widely recognized for its bioactive extract and essential oil, which exhibit a range of health-promoting effects. Traditionally, lemongrass has been utilized in food products and herbal infusions because of its distinctive citrus-like aroma and potential therapeutic benefits (Boeira et al., 2018; Tariq et al., 2021; Ullah et al., 2020). Lemongrass (LG) extracts have been reported to exhibit strong antioxidant, anti-inflammatory, and anticancer activities, primarily due to their high phenolic content. These bioactive compounds contribute to the reduction of oxidative stress and show considerable potential as natural replacements for synthetic additives in food products (Pan et al., 2022; Ruvinov et al., 2019). The incorporation of plant-derived extracts into food products has attracted increasing attention as a strategy to

enhance both shelf life and nutritional quality. In this context, LG extracts have demonstrated considerable potential as natural antioxidant and antimicrobial agents, contributing to improved oxidative stability and microbial safety in meat products and lipid-rich food systems. Nevertheless, the efficacy of these extracts is strongly influenced by the extraction method employed, as the recovery and preservation of phenolic compounds from plant matrices are critical determinants of their functional performance (Boeira et al., 2018; Falah et al., 2015). Despite the development of advanced extraction technologies, maceration and percolation continue to be extensively utilized because they are advantageous for their operational simplicity and practical applicability. However, the limitations of these methods, particularly prolonged processing times, high solvent demand, and suboptimal extraction efficiency, continue to drive the development of alternative extraction approaches. Therefore, the demand for sustainable and innovative approaches that improve yield while minimizing processing time and energy use is increasing (Rasul, 2018).

*Corresponding Author: Professor, Department of Food Science and Technology, School of Agriculture, Shiraz University, Shiraz, I. R. Iran

E-mail address: niakosar@shirazu.ac.ir

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In recent years, ohmic heating has emerged as a sustainable and efficient extraction method for isolating bioactive compounds, extracts, and essential oils from medicinal plant materials. In this process, the application of an electric current to the sample induces rapid and even volumetric heating as a result of its inherent electrical resistance (Al-Hilphy et al., 2015; Irfan et al., 2022). One of the principal benefits of ohmic heating-assisted extraction (OHE) is the induction of electroporation within plant tissues, which increases cell membrane permeability and promotes the efficient extraction of intracellular bioactive constituents. Beyond its ability to improve extraction performance, ohmic heating offers significant advantages in terms of reduced processing time and energy requirements, as well as accurate control over operational variables such as voltage, temperature, and electric field intensity. These benefits have facilitated its application in various food-processing operations, including blanching, pasteurization, and the recovery of pectin, pigments, essential oils, and inulin (Ferreira-Santos et al., 2024; Talha et al., 2024). Recent studies have highlighted the potential of OHE for extracting bioactive compounds from by-products. OHE reduced processing time and energy consumption by up to 50% and 80%, respectively, increased phenolic compound recovery by approximately 40%, and demonstrated superior extraction performance compared with conventional extraction techniques (Gavahian & Chu, 2022b; Sánchez et al., 2023; Shahidi et al., 2020). Despite its promising benefits, OHE has rarely been applied to the extraction of phenolic compounds from LG, and no comprehensive study has yet examined the combined effects of solvent type, solvent concentration, operating temperature, and sample-to-solvent ratio on extraction performance. Despite the growing interest in OHE, its application for phenolic extraction from LG has received limited attention. Therefore, this study investigated, for the first time, the effects of ethanol concentration, operating temperature, and LG-to-solvent ratio on the extraction efficiency of phenolic compounds using OHE. The performance of optimized OHE was subsequently compared with conventional maceration (ME) and magnetic stirring extraction (MSE) based on total phenolic content, total flavonoid content, and antioxidant activity. The findings provide insights into the potential of OHE as an efficient and environmentally friendly approach for producing functional plant extracts.

MATERIALS AND METHODS

Plant materials

Fresh LG leaves were harvested from a plantation in Firoozabad (Fars, Iran), shade-dried to about 8% moisture, packed in polyethylene bags, and then stored in a cold room until they were needed for analysis and further use. The plant material used in this study was identified as *Cymbopogon citratus* (DC.) Stapf by a qualified botanist. The taxonomic authentication was based on the reference specimen deposited at the Herbarium of the Faculty of Pharmacy, Tehran University of Medical Sciences (Herbarium No. 6603-TEH).

Lemongrass extraction

Ohmic heating extraction (OHE)

The LG leaves were first ground and passed through an 18-mesh sieve before extraction. For the OHE, different process parameters, including LG-to-solvent ratio (1:10, 1:15, and 1:20), operating temperature (50 and 70 °C), and ethanol concentration (50% and 70% v/v) were investigated to optimize TPC. The LG leaves were ground and sieved through an 18-mesh screen prior to extraction. In OHE, the process was optimized for total phenolic content (TPC) by varying the LG-to-solvent ratio (1:10, 1:15, and 1:20), extraction temperature (50 and 70 °C), and ethanol concentration (50% and 70% v/v). These conditions were selected based on literature reports on *Cymbopogon citratus* and related medicinal plants, as well as preliminary trials. All extractions were performed for 1 h at a constant electric field strength of 15 V cm⁻¹ and a voltage of 270 V, using platinum electrodes with an 18 cm gap. The resulting mixtures were centrifuged (K2015R, Centurion Scientific Ltd., UK) at 2200 × g for 11 min and filtered to remove insoluble residues. Residual ethanol was removed using a rotary vacuum evaporator (IKA RV10 DS99, Germany) at 40 °C, followed by freeze-drying of the extracts (FD-5003-BT, Dena Vacuum, Iran). The dried powders were then stored in airtight, light-protected glass containers at 4 °C for further analysis (Pereira et al., 2021; Seidi Damyeh et al., 2016).

Magnetic stirrer extraction (MSE)

Based on the optimized OHE conditions, magnetic stirring extraction (MSE) was conducted using 50% (v/v) ethanol, an LG-to-solvent ratio of 1:10, and a temperature of 50 °C on a magnetic stirrer (L81, Labinto, Netherlands) for 1 h (Boeira et al., 2018).

Maceration extraction (ME)

To perform maceration extraction (ME), dried LG leaves were mixed with the solvent at room temperature under sealed, light-protected conditions to prevent ethanol loss and extracted for 72 h using the same ethanol concentration and LG-to-solvent ratio as MSE. The extracts were then purified and converted into powders following the same procedure as OHE.

Electrical conductivity (EC)

Due to the key role of the electrical conductivity (EC) of LG leaf-solvent mixtures in heat generation during OHE, EC was measured prior to extraction using a conductometer (Model 644, Metrohm, Switzerland) and expressed in µS/cm (Ferreira-Santos et al., 2024). Measurements were performed at 25 °C and an LG-to-solvent ratio of 1:10.

Dry matter

The dry matter content of the extracts was determined by collecting 5 mL of each sample after centrifugation and filtration. The samples were then dried in a laboratory oven at 105 °C until a constant weight was

reached (Chen et al., 2007). The dry matter percentage was calculated using Eq. (1):

$$\text{Dry matter (\%)} = (A - B) / C \times 100 \quad \text{Eq. (1)}$$

Where A is the initial weight of the extract along with the glass Petri dish, B is the weight of the extract and Petri after drying, and C is the original weight of the extract alone.

Total phenolic content (TPC)

The total phenolic content (TPC) was determined following the modified method of Shadid et al. (2021). Briefly, an aqueous solution of the freeze-dried extract (1 mg mL^{-1}) was prepared, and $125 \text{ }\mu\text{L}$ was mixed with $625 \text{ }\mu\text{L}$ of 10% (v/v) Folin–Ciocalteu reagent and incubated for 5 min. Subsequently, $625 \text{ }\mu\text{L}$ of sodium bicarbonate solution (7.5%, w/v) was added, and the mixture was kept at 45°C for 45 min. Absorbance was then measured at 765 nm using a 96-well microplate reader (Citation™3, BioTek, USA), with gallic acid (GA) as the standard. Distilled water was used as the control. A calibration curve was constructed over the concentration range of $0.02\text{--}0.1 \text{ mg mL}^{-1}$. Results were expressed as mg gallic acid equivalents per g of dry matter (mg GAE/g d.m.) (Lutz et al., 2015; Shadid et al., 2021).

Total flavonoid content (TFC)

Total flavonoid content (TFC) was determined by mixing $500 \text{ }\mu\text{L}$ of extract (1 mg mL^{-1}) with $500 \text{ }\mu\text{L}$ of 2% AlCl_3 solution, followed by incubation in the dark for 1 h. Absorbance was measured at 420 nm using a 96-well microplate reader. A quercetin calibration curve ($2\text{--}40 \text{ }\mu\text{g mL}^{-1}$) was used for quantification. All solutions were prepared in 70% (v/v) ethanol. Results were expressed as mg quercetin equivalents per g of dry matter (mg QE/g d.m.) (Paudel et al., 2015).

Antioxidant activity (AA)

The antioxidant activity (AA) of the freeze-dried extract was evaluated using the DPPH radical scavenging assay, based on the reduction of DPPH radicals accompanied by a color change from purple to yellow. A $50 \text{ }\mu\text{g mL}^{-1}$ solution of LG extract was prepared in 50% (v/v) ethanol, and 1 mL of this solution was mixed with 1 mL of DPPH solution. The mixture was incubated in the dark at 25°C for 1 h. Absorbance was measured at 517 nm , and the inhibition percentage was calculated using Eq. (2) (Yılmaz & Bilek, 2018):

$$\text{Inhibition (\%)} = (A - B) / A \times 100 \quad \text{Eq. (2)}$$

Where A is the absorbance of the control (a 50% ethanol solution), and B is the absorbance of the sample.

Microstructure analysis

The microstructure of LG leaves before and after extraction using OHE, MSE, and ME was examined by scanning electron microscopy (SEM) (Vega3, TESCAN, Czech Republic) at an accelerating voltage of 20 kV . Leaf samples

were mounted on conductive stubs and coated with a thin gold layer. Images were acquired at $1000\times$ magnification (Sarah et al., 2023).

Specific energy consumption (SEC)

The specific energy consumption (SEC) for OHE and MSE was measured using a digital kWh meter (AMPY C.F.Z. 5194, Iran; accuracy 0.01 kWh) installed in-line between the main power supply and each system to record total energy use during processing. Energy consumption was expressed as kWh per kg of sample (Baeghbali et al., 2019).

HPLC-MS analysis of LG extract

LC–MS analysis was carried out to identify the phytochemical profile of the optimized OHE extract of LG. For sample preparation, the extract powder was dissolved in methanol (1:10, w/v), diluted with water, centrifuged at $10,000 \text{ rpm}$ for 10 min, and the supernatant was filtered through a $0.45 \text{ }\mu\text{m}$ syringe filter. Chromatographic separation was performed using a Waters Alliance 2695 HPLC system equipped with a Eurospher C18 column ($4.6 \times 120 \text{ mm}$, $5 \text{ }\mu\text{m}$). The injection volume was $5 \text{ }\mu\text{L}$, with a flow rate of 0.3 mL min^{-1} and a column temperature of 35°C . The mobile phase consisted of solvent A (acetonitrile with 0.1% formic acid) and solvent B (water with 0.1% formic acid) under a gradient program: 0–2 min, 10% A/90% B; 10–20 min, 70% A/30% B; and 22–25 min, 10% A/90% B. Mass spectrometric detection was conducted using a Micromass Quattro Micro API system with electrospray ionization (ESI) in negative ion mode. The operating parameters included a cone voltage of 25 V , capillary voltage of 4 kV , extractor voltage of 3 V , RF lens voltage of 0.1 V , source temperature of 120°C , desolvation temperature of 350°C , and nitrogen (grade 5) as nebulizing gas at 200 L h^{-1} . Compounds were tentatively identified based on retention times and $[\text{M}-\text{H}]^-$ ions, in comparison with literature and database information. Data acquisition and processing were performed using MassLynx V4.1 software.

Statistical analysis

All experiments were performed in three independent replicates, and the results are presented as mean $\pm$ standard deviation (SD). Statistical analysis was carried out using analysis of variance (ANOVA), followed by Duncan's multiple range test to determine significant differences among means ($P < 0.05$). Data processing was conducted using SPSS software (version 9.4; SAS Institute Inc., Cary, NC, USA).

RESULTS AND DISCUSSION

Electrical conductivity (EC)

The electrical conductivity (EC) of the different extraction media is shown in Table 1. Incorporation of milled LG leaves into the solvents increased the EC of the extraction mixtures. This observation agrees with previous findings indicating that ionic strength and medium composition contribute significantly to enhanced ohmic heating performance (Gavahian and Chu, 2022a). Consequently, the LG–solvent mixtures exhibited sufficient electrical

conductivity for effective ohmic heating, eliminating the need for NaCl supplementation to increase EC, as reported in some earlier studies. Seidi Damyeh et al. (2016) reported the addition of NaCl during ohmic-assisted extraction of essential oil from *Satureja macrosiphonia* to enhance the electrical conductivity of the extraction medium and facilitate more rapid attainment of the desired processing temperature. As shown in Table 1, the 50% (v/v) ethanol solution exhibited the highest electrical conductivity (EC), whereas increasing the ethanol concentration in the solvent mixture resulted in a marked decline in EC. In general, hydroethanolic solvents are preferred to absolute ethanol (100% v/v) for ohmic heating extraction applications, as also observed by Moongngarm et al. (2022). This preference is likely attributable to the inherently low electrical conductivity of absolute ethanol, which limits its suitability for efficient ohmic heating.

Table 1. Electrical conductivity of various extraction media used in ohmic heating extraction

Solution	Electrical conductivity ($\mu\text{S cm}^{-1}$)
Distilled water	22.71 ± 0.01
Ethanol (96%)	1.40 ± 0.03
Ethanol (70%)	9.85 ± 0.07
Ethanol (50%)	15.71 ± 0.02
LG dried leaves and ethanol (50%) (1:10 ratio)	2269.80 ± 0.45
LG dried leaves and ethanol (70%) (1:10 ratio)	1489.32 ± 0.43

Data presents the mean $\pm$ SD

Optimization of OHE

The OHE process was optimized based on the TPC of the extracts. This approach prioritizes the recovery of phytochemicals with high bioactive and therapeutic potential rather than simply maximizing the overall extract yield. Overall, the extraction conditions markedly influenced both extraction efficiency and the recovery of bioactive constituents from lemongrass leaves. The dry matter contents obtained under different OHE conditions are presented in Table 2. The OHE system produced extracts with dry matter yields of up to 4.31%, which may be attributed to electroporation-induced structural changes in plant tissues. These changes generate pores and microcracks that enhance solvent penetration and facilitate the release of intracellular compounds (Moongngarm et al., 2022). The highest dry matter yields were achieved under two extraction conditions: a lemongrass-to-solvent ratio of 1:10 using 50% ethanol at 70 °C, and the same ratio using 70% ethanol at 50 °C. In contrast, the lowest dry matter yield was observed at a 1:20 ratio with 70% ethanol at 70 °C. These findings indicate that, at a given ethanol concentration and extraction temperature, increasing the solvent-to-solid ratio from 10:1 to 20:1 reduced the dry matter concentration of the resulting extracts. Furthermore, the results underscore the importance of extraction parameters, particularly solvent composition, in determining extraction performance. Similar observations were reported by Pereira et al. (2021), who demonstrated that solvent composition significantly affects the recovery of bioactive compounds from *Gracilaria vermiculophylla* using both ohmic-assisted and conventional extraction techniques.

Furthermore, a higher dry matter yield did not necessarily correspond to a higher TPC (Table 2). Dry matter represents the cumulative extraction of phenolic compounds as well as other constituents from the lemongrass matrix. This was evident from the extraction condition of a 1:10 LG-to-solvent ratio with 50% ethanol at 50 °C, which yielded the highest TPC despite not producing the greatest dry matter content. The discrepancy may be attributed to the co-extraction of non-phenolic compounds, including carbohydrates, proteins, pigments, and other soluble constituents.

As shown in Table 2, the optimal extraction conditions were a LG-to-solvent ratio of 1:10, a temperature of 50 °C, and a hydroethanolic solvent containing 50% (v/v) ethanol. Under these conditions, the highest TPC was achieved, reaching 85.83 ± 2.28 mg gallic acid equivalents (GAE)/g dry matter, while the dry matter yield remained relatively moderate at approximately 3.3%. Consequently, these conditions were selected for subsequent extraction experiments using maceration and magnetic stirring techniques.

Table 2. Total phenolic content (TPC) and dry matter of lemongrass (LG) leaves extracts

Extraction conditions	TPC (mg GA eq/g d.m.)	Dry matter (%)
1:10, 50%, 50 °C*	85.83 ± 2.28^a	3.30 ± 0.10^{bc}
1:10, 50%, 70 °C	61.43 ± 5.94^c	4.02 ± 0.01^a
1:10, 70%, 50 °C	63.22 ± 4.93^c	4.31 ± 0.04^a
1:10, 70%, 70 °C	78.68 ± 4.30^b	2.96 ± 0.07^{cd}
1:15, 50%, 50 °C	53.39 ± 0.38^d	3.10 ± 0.01^{bcd}
1:15, 50%, 70 °C	38.91 ± 0.88^e	3.55 ± 0.63^b
1:15, 70%, 50 °C	41.86 ± 0.76^e	3.15 ± 0.04^{bc}
1:15, 70%, 70 °C	50.89 ± 0.63^d	2.89 ± 0.10^{cd}
1:20, 50%, 50 °C	52.59 ± 0.25^d	3.07 ± 0.02^{cd}
1:20, 50%, 70 °C	38.73 ± 0.63^e	3.14 ± 0.06^{bc}
1:20, 70%, 50 °C	39.99 ± 0.88^e	3.12 ± 0.03^{bcd}
1:20, 70%, 70 °C	40.52 ± 1.14^e	2.67 ± 0.05^d

*LG to solvent ratio; ethanol concentration and operating temperature. (Data presents the mean $\pm$ SD. Different superscripts indicate significant differences at $P < 0.05$).

Previous studies have similarly emphasized the importance of extraction parameters in maximizing phenolic recovery. For instance, Muniz-Márquez et al. (2013) reported that reducing the solid-to-liquid ratio from 1:4 to 1:12 significantly improved the extraction of phenolic compounds from *Laurus nobilis*. In general, extraction efficiency is influenced by the extraction technique, operating conditions, and the physicochemical characteristics of the plant matrix, highlighting the necessity of optimizing extraction conditions for each specific material. In contrast, Jovanović et al. (2021) found that ethanol concentrations of 30%, 50%, and 70% had no significant effect on the polyphenol content of wild thyme extracts obtained by ultrasound-assisted extraction. However, in the case of lemongrass, the LG-to-solvent ratio appears to be a more influential factor, affecting both total phenolic content (TPC) and radical scavenging activity. This observation is consistent with the findings of Muala et al. (2021), who reported a positive relationship between the solid-to-liquid ratio and both TPC and DPPH radical scavenging activity in lemongrass extracts.

The present results also agree with those of Safarzadeh Markhali et al. (2022) who demonstrated that ohmic heating

extraction of olive leaves at 55 °C using 60% ethanol yielded the highest TPC. Nevertheless, these conditions did not correspond to the maximum extraction yield or antioxidant activity. Such findings underscore the critical influence of extraction temperature on phenolic recovery, the effect of which is strongly dependent on the characteristics of the plant matrix. While moderate temperature increases can enhance mass transfer and facilitate the release of intracellular compounds, excessive temperatures may promote the degradation of thermolabile phenolics. In the present study, the superior performance of 50% ethanol may be attributed to the relatively high polarity of lemongrass phenolic compounds and the enhanced electrical conductivity of the hydroethanolic solvent under OHE conditions. Improved conductivity facilitates more uniform volumetric heating, thereby enhancing extraction efficiency. Given the structural diversity and varying polarities of phenolic compounds, solvent selection remains one of the most critical and challenging aspects of extraction process optimization (Safarzadeh Markhali et al., 2022).

Comparative analysis of extraction techniques for lemongrass leaf

The choice of extraction method clearly influenced both how efficient the process was and how much of the bioactive compounds could be recovered from the lemongrass leaves. Based on the results presented in Table 2, the optimum extraction conditions of OHE were selected for the other two extraction methods, and the dry matter content, TPC, TFC, and AA of LG leaf extracts obtained using these different extraction techniques were compared.

As presented in Table 3, the OHE system yielded extracts with dry matter contents exceeding 3%, which was significantly higher ($P < 0.05$) than that obtained by maceration (approximately 1.5%). The higher level of soluble solids in the OHE extracts can be attributed to electroporation effects, which induce the formation of pores and microcracks in plant tissues, thereby enhancing solvent penetration and facilitating the release of intracellular constituents. This structural disruption was particularly evident in the residual plant material after OHE treatment and was further confirmed by SEM analysis. As shown in Fig. 1, ohmic-treated leaves (Fig. 1c) exhibited pronounced microstructural alterations compared with the largely intact cellular structures observed in untreated samples (Fig. 1a), microwave-assisted extraction (MSE) samples (Fig. 1b), and maceration extracts (Fig. 1d).

Table 3. Dry matter content, TPC, TFC, and AA of lemongrass leaf extracts from different extraction methods

Extraction method	Dry matter (%)	TPC (mg GA eq/g d.m.)	Flavonoids (mg Qu/g d.m.)	Inhibition (%) at 50 µg mL ⁻¹
OHE*	3.30 ± 0.10 ^a	85.83 ± 2.28 ^a	17.46 ± 0.18 ^b	44.95 ± 1.75 ^a
MSE	2.21 ± 0.03 ^b	81.26 ± 0.37 ^b	19.06 ± 0.03 ^a	41.01 ± 1.27 ^b
ME	1.47 ± 0.06 ^c	79.10 ± 0.49 ^b	15.51 ± 0.68 ^c	39.85 ± 1.59 ^b

*OHE: ohmic heating extraction, MSE: magnetic stirrer extraction, ME: maceration extraction (Data presents the mean ± SD. Different superscripts indicate significant differences at $P < 0.05$).

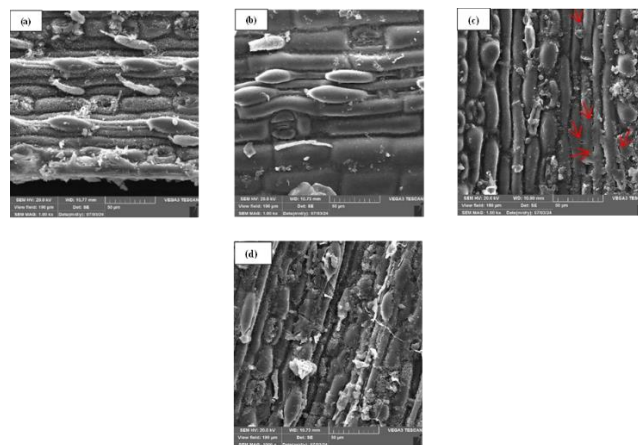


Fig. 1. SEM micrograph of lemongrass leaves at 1000× magnification: (a) prior to extraction, (b) after magnetic stirrer extraction, (c) ohmic heating extraction, and (d) maceration extraction.

The TPC obtained under the optimized OHE conditions was further compared with that of conventional extraction methods (Table 3). Both (ME) and (MSE) produced significantly lower TPC values (81.26 ± 0.37 and 79.10 ± 0.49 mg gallic acid equivalents (GAE)/g dry matter, respectively) than OHE (85.83 ± 2.28 mg GAE/g dry matter) ($P < 0.05$). The superior performance of OHE can be attributed to electroporation, which induces the formation of pores and microcracks in plant tissues. These structural modifications enhance solvent penetration and promote the release of intracellular phenolic compounds (Moongngarm et al., 2022). This phenomenon was clearly observed in SEM micrographs, where OHE-treated lemongrass leaves (Fig. 1c) showed pronounced structural damage, whereas the tissue architecture remained largely intact in MSE and ME samples (Fig. 1b and 1d, respectively). In contrast, the total flavonoid content (TFC) of the freeze-dried extract obtained by MSE reached 19.06 ± 0.03 mg quercetin equivalents (QE)/g dry matter, which was significantly higher ($P < 0.05$) than that obtained by OHE (17.46 ± 0.18 mg QE/g dry matter) and ME (15.51 ± 0.68 mg QE/g dry matter) (Table 3). Since MSE and OHE were conducted under identical time and temperature conditions, with the exception of the application of a 270 V electric field in OHE, the lower TFC observed in OHE may be attributed to prolonged exposure to electrically induced heating, which could promote the degradation of thermolabile flavonoids. A similar reduction in flavonoid recovery has been reported in lemongrass extracts obtained by ultrasound-assisted extraction compared with conventional methods (Boeira et al., 2018). As shown in Table 3, at a concentration of 50 µg/mL, the OHE extract exhibited the highest DPPH radical scavenging activity ($44.95 \pm 1.74\%$), which was significantly greater ($P < 0.05$) than that of MSE ($41.01 \pm 1.27\%$) and ME ($39.85 \pm 1.59\%$). These results indicate that OHE enhances the antioxidant potential of the extracts. Similar trends have been reported in recent studies, where OHE consistently yielded extracts with improved antioxidant activity (Ferreira-Santos et al., 2024).

Regarding energy consumption, the OHE and MSE processes under optimal conditions required 0.05 kWh and 0.06 kWh, corresponding to 1.25 and 1.5 kWh per kg

of dry freeze-dried sample, respectively. The lower energy demand of OHE is mainly associated with its rapid heating capability, which reduces the time needed to reach the target extraction temperature. In contrast, the ME process involved no electrical input or active agitation, resulting in negligible energy consumption. Therefore, further optimization of the OHE system, such as increasing electrode surface area or improving internal mixing, along with the refinement of other process parameters, is expected to reduce processing time and enhance energy efficiency. Similar observations were reported by Gavahian and Chu (2022a), who demonstrated that OHE reduces energy requirements during the extraction of bioactive compounds from pineapple peels due to shortened come-up time, with electrode design and applied voltage playing key roles in heating performance.

LC-MS analysis of OHE hydroethanolic extract

LC-MS analysis performed in negative ion mode identified 22 chromatographic peaks, which were tentatively assigned to 25 phytochemical constituents in the LG extract obtained via OHE (Table 4). The detected compounds were predominantly classified as phenolic acids, flavonoids, and their derivatives. Identified metabolites included protocatechuic acid, caffeic acid, chlorogenic acid, p-coumaric acid, and derivatives of kaempferol, apigenin, and quercetin, all of which have been previously linked to antioxidant activity. According to the literature, compounds such as p-coumaric acid, chlorogenic acid, and quercetin-3-glucoside are among the major flavonoids reported in lemongrass and were also detected in relatively higher abundance in the present extract. Collectively, these bioactive constituents contribute to the medicinal value of lemongrass, which has been associated with various health-promoting properties, including anti-diabetic, anti-inflammatory, antimicrobial, and anticancer activities (Kiani et al., 2022). However, certain compounds previously reported in lemongrass, such as syringic acid and hesperidin, were not detected under the current experimental conditions. This absence may be attributed to variations in plant material origin, extraction parameters, or concentrations falling below the detection threshold of the analytical method (Ali et al., 2022; Kiani et al., 2023).

CONCLUSION

Advancements in efficient and sustainable extraction technologies is essential for reducing energy consumption, enhancing extraction yields, and improving overall process economics. *Cymbopogon citratus* (lemongrass) is a widely recognized medicinal and culinary plant that serves as a promising natural source of antioxidant compounds. Its extracts can be effectively incorporated into food systems to enhance oxidative stability, decrease reliance on synthetic additives, and provide additional health-promoting properties. In terms of extraction performance, the present study demonstrates that ohmic heating extraction is an

effective technique for maximizing the recovery of phenolic compounds and antioxidant activity from lemongrass leaves, while also contributing to reduced energy requirements. However, the thermal sensitivity of certain flavonoids must be taken into consideration, indicating that careful optimization of process parameters such as voltage, temperature, and extraction time is necessary to preserve a broad spectrum of bioactive constituents. Overall, the synergistic effects of enhanced cell disruption, solvent-matrix interactions, and process efficiency provide a strong mechanistic basis for the application of ohmic heating as a promising and efficient approach for the extraction of functional phytochemicals.

Table 4. LC-ESI-MS identification of phytochemical metabolites from ohmic-assisted extraction of LG leaves

Peak NO.	Retention Time (min)	[M-H] ⁻ (m/z)	Tentatively identified compound
1	4.94	368.96	Ferulic acid 4-O-glucuronide
2	3.10	471.16	4"-O-Methylepigallocatechin 3-O-gallate
3	5.11	367.11	3-Feruloylquinic acid
4	11.89	693.43	1,2-Diferuloylgentiobiose
5	11.44	576.81	Procyanidin B2
6	10.59-11.02	593.19	*Didymin & Apigenin 6,8-di-C-glucoside
7	10.37-11.50	578.99	*Naringin & Kaempferol 3-O-xylosyl-glucoside
8	3.11	341.02	Tetramethylscutellarein
9	11.08	563.28	Apigenin 6,8-C-arabinoside-C-glucoside
10	10.79-11.26	447.12	*6-Hydroxyluteolin 7-O-rhamnoside & Kaempferol 3-O-glucoside
11	11.48	237.12	6-Hydroxyflavone
12	11.24	401.14	3-Methoxysinensetin
13	10.65	548.81	Quercetin 3-O-(6-malonyl)-glucoside
14	3.13	386.98	Trachelogenin
15	10.42	353.05	Chlorogenic acid
16	12.11	163.03	p-Coumaric acid
17	3.28	179.01	Caffeic acid
18	2.81	288.96	Catechin
19	13.75	284.95	Kaempferol
20	10.84	252.99	Daidzein
21	11.40	152.98	Protocatechuic acid
22	11.26	176.90	Esculetin

*Identification of some compounds remained ambiguous due to identical precursor ions and the absence of confirmatory MS/MS fragmentation data.

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CRediT AUTHORSHIP CONTRIBUTION STATEMENT

Conceptualization: Fatemeh.Goli and Mehrad.Niakousari; Methodology: Fatemeh.Goli and Mehrad.Niakousari; Software: Fatemeh.Goli; Validation: Fatemeh.Goli and

Mehrad.Niakousari and Fatemeh.Ghiasi and Marzieh. Moosavi-Nasab; Formal analysis: Fatemeh.Goli; Investigation: Fatemeh.Goli and Mehrad.Niakousari and Fatemeh.Ghiasi; Resources: Mehrad.Niakousari and Fatemeh.Ghiasi and Marzieh. Moosavi-Nasab; Data curation: Fatemeh.Goli; Writing—original draft preparation: Fatemeh.Goli; Writing—review and editing: Mehrad.Niakousari and Fatemeh.Ghiasi and Marzieh.Moosavi-Nasab; Visualization: Fatemeh.Goli; Supervision: Mehrad.Niakousari; Project administration: Mehrad.Niakousari; Funding acquisition: Mehrad.Niakousari.

DECLARATION OF COMPETING INTEREST

The authors declare no conflicts of interest.

ETHICAL STATEMENT

This study did not involve any experiments or research on humans or animals.

DATA AVAILABILITY

Data will be made available on request.

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