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Effect of Adding Soybean Flour on The Rheological Properties of Wheat Flour Dough

Suleiman Mohammed Abdel[1*]
[1]Botany Department, Faculty of Science, University of Derna, Al-Qubba, Libya

تأثير إضافة خزان الصرف الصحي إلى الأرضية وإزالة جميع خصائص الأرضية

سليمان محمد عبد السميع [1*]
[1]قسم النبات، كلية العلوم، جامعة درنة، القبة، ليبيا

[*]Corresponding author: Silman55@yahoo.com

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Abstract:
Different type of plants grow across Libya and among them there are plants used for medicinal and aromatic purposes and have been used by Libyans for ages in their traditional as well as modern practices. Several researches on the plants have been undertaken to determine the proximate composition, phytochemicals, and the biological of the plants. For instance, studies have showed that the oils from species such as Haplophyllum tuberculatum, Artemisia herba alba and Thymus capitatus possess variable biological properties including; antibacterial, anti-inflammatory and healing properties. All these bioactivities support the recognition of the value of Libyan plants in treating a myriad of diseases. An important feature of these plants is variability in the composition of the essential oils within a specific season as it is evident in the total flavonoids content in Haplophyllum tuberculatum which determines the plant's effectiveness in tackling certain ailments. There is a good chronical of the antimicrobial effects of the extracts of some plants like Juniperus phoenicea and Rosmarinus officinalis also points to how Libyan plants may helpful in the treatment of common infections and boost the immune system. That has inclined researchers to turn to these plants as possible sources for the creation of new natural drugs and functional foods. Subsequent research on the therapeutic uses of these plants has created opportunities for new findings in the formulation of nanoemulsion gel, used in the treatment of wound.

Keywords: Libyan flora, medicinal plants, aromatic plants, essential oils.

الملخص
تنمو أنواع مختلفة من النباتات في جميع أنحاء ليبيا، ومن بينها نباتات تستخدم للأغراض الطبية والعطرية وقد استخدمها الليبيون على مر العصور في ممارساتهم التقليدية والحديثة. تم إجراء العديد من الأبحاث على النباتات لتحديد التركيب التقريبي والمواد الكيميائية النباتية والبيولوجية للنباتات. على سبيل المثال، أظهرت الدراسات أن الزيوت المستخرجة من أنواع مثل *Haplophyllum tuberculatum*، *Artemisiaherba alba* و *Thymus capitatus* تمتلك خصائص بيولوجية متغيرة بما في ذلك؛ خصائص مضادة للجراثيم ومضادة للالتهابات والشفاء. كل هذه الأنشطة الحيوية تدعم الاعتراف بقيمة النباتات الليبية في علاج عدد لا يحصى من الأمراض. من السمات المهمة لهذه النباتات هو التباين في تركيبة الزيوت العطرية خلال موسم معين كما يتضح من إجمالي محتوى الفلافونويد في هابلوفيلوم توبركولاتوم والذي يحدد مدى فعالية النبات في معالجة بعض الأمراض. هناك سجل جيد للتأثيرات المضادة للميكروبات لمستخلصات بعض النباتات مثل *Juniperus phoenicea* و*Rosmarinus officinalis* ويشير أيضًا إلى كيف يمكن للنباتات الليبية أن تساعد في علاج الالتهابات الشائعة وتعزيز جهاز المناعة. وقد دفع ذلك الباحثين إلى اللجوء إلى هذه النباتات كمصادر

محتملة لإنتاج أدوية طبيعية جديدة وأغذية وظيفية. وقد خلقت الأبحاث اللاحقة حول الاستخدامات العلاجية لهذه النباتات فرصًا لنتائج جديدة في تركيب هلام المستحلب النانوي المستخدم في علاج الجروح.

الكلمات المفتاحية: النباتات الليبية، النباتات الطبية، النباتات العطرية، الزيوت العطرية.

Introduction

Wheat flour is a fundamental ingredient in the production of various bakery products due to its unique rheological properties, which contribute to dough elasticity, extensibility, and overall baking performance. However, wheat flour alone may not always provide sufficient nutritional balance, particularly in terms of protein content and essential amino acids. In response to this, there has been growing interest in incorporating alternative protein sources, such as soybean flour, into wheat-based products to enhance their nutritional value and functional properties [1]. Soybean flour is known for its high protein content, essential amino acids, and functional properties that can influence dough behavior. The addition of soybean flour to wheat flour dough can impact key rheological parameters, including viscosity, elasticity, and water absorption capacity, which ultimately affect dough handling, fermentation, and final product quality.

Understanding these effects is essential for optimizing formulations that maintain desirable dough characteristics while improving the nutritional profile of wheat-based products. Since Libya has different geographical zones from plains in the coastal zone to mountainous regions, it boasts of different essential and medicinal plants. Such plants include Thymus capitatus, Rosmarinus officinalis and Juniperus phoenicea, which demonstrated moderate to high possibility of essential oil yield [1]. Nonetheless, the approach for isolating crucial oils determines their quantity, constitution, and functionality; consequently, the selection of the extraction approach is a real determinant defining the potential of crucial oils [2].

Hydrodistillation is up till today the most frequented methods in the use and management for its simplicity in acquisition and application. However, these methods are also slower, more energy demanding, and provide a poorer conservation of thermolabile compounds. The use of microwave adsorbed extraction (MAE), ultrasonic extraction (UAE) and supercritical fluid extraction (SFE) is relatively recent advancements and are more efficient and more friendly to environment than the traditional methods [3]. Such techniques have revealed higher efficiency and effectiveness both in the yield percentage and energy utilized as well as the conservation of bioactive compounds in different investigate studies [4].

Since Libya is endowed with so many untapped aromatic plants and there is rapidly growing market demand for quality essential oils all over the world, this study aims at assessing and comparing the efficiency of these innovative extraction methods [5]. Through quantitative analyses of oil yield percentage, energy consumption, and chemical compositions of extracted essential oils, as well as qualitative analyses of the impacts of these extracts on microorganisms and environment, the study seeks to determine the appropriate technique to apply in liberating essential oils from plants in Libya [6]. This work also helps to expand the existing body of scientific knowledge regarding the extraction of essential oil and also helps to consult with the sustainable yield's natural resources in Libya for the locals and international markets.

Methodology

The essential oils from Libyan plants are developed using new approaches in a systematic interdisciplinary way. The approach begins by selecting and collecting native plants that show the possibility for extraction of essential oil, based on traditional uses of the plants in Libya, presence of compound aromatic, according to previous research done, and sustainability of the extraction method to harvest a plant from its natural habitat. These conditions and considerations are subsequently filed expeditions under different locations of Libya like coastal plains, deserts, or mountains to cover diversity in sampling. GPS mapping and ecological field documentation take place here alongside these collections to provide context for the plants' origin.

In any case, once harvested the plants are processed as soon as possible to ensure that the correct volatile oils are not compromised. They qualify shaving the plant materials and washing them to eliminate dirt and other elements then proceed to drying in proper structures such as shade drying or freeze-drying equipment in order to avoid deterioration of other vital oils. After that, the dried plant material is reduced into fine particles to facilitate extraction of the components. Drying methods are compared and their effectiveness in the yields and quality of the extracted oils is assessed. The heart of this research study revolves around the generation and enhancement of different extraction methods. Conventional hydrodistillation can be replaced by adjusting such factors as distillation period, temperature, volume of distilled water for plant material, etc., and using an adapted Clevenger device to enhance the yield of the oil.

MAE and UAE are two of the modern methods that are also discussed. These methods employ microwave energy or ultrasonic waves respectively to cause the liberation of essential oil from the plant material. The study further focuses on the Supercritical fluid extraction (SFE) whereby carbon dioxide at supercritical conditions extracts oils without heat assignment. Each method, for power intensity, temperature, pressure factors have systematically tuned for different plant types. In the case of each technique, the efficiency of the extraction, energy and the effects of the technique on the environment is evaluated. By chemical and sensory analysis, the extracted oils are evaluated in terms of quality nad to determine their constituents. GC-MS helps to analyse and determine the concentration of volatile compounds in the oils, while the identification of the functional groups in the oils is defined using FTIR. Non-volatile components are identified with the use of High-performance liquid chromatography (HPLC) and sensory evaluation is employed to rate the oils based on fragrances. These analysis assists in defining the best method to use when extracting each plant.

A comparative review of different extraction methods is based on oil yield, purity of the extracted compounds, cost efficiency, and environmental sustainability. Statistical analyses such as Analysis of Variance (ANOVA) would identify methods that show significant differences from one another and confirm the statistics for the reviews. Ultimately, the best methods are scaled up for pilot testing to find out their feasibility for commercial production and collaborating with local industries and cooperatives would be explored to ensure the practical application of these methods toward sustainable use of Libyan plant resources. This methodological framework aims to ensure the extraction of essential oils, conserve biodiversity, and enhance the socio-economic development of the area.

Data Collection

This paper reveals that data collection is an important factor in determining new techniques for extracting essential oils from plants in Libya. This work starts with the choice of plant species, and depends on the ability of species to produce the essential oil with reference to their ethno pharmacological uses, literature records of aromatics, and adaptability in their natural environment. Fifty species are shortlisted from a preliminary review, with collection conducted across five ecological zones: including coastal plains, deserts, mountains, valleys and oases. All the zones collectively provide 20 percent of the total species collected for which there are 10 species per zone.

The samples are collected from 50 individuals for each selected species, which amounts to 500 samples for screening purposes at first instance. GPS is used in each collection site of different artefacts to record the latitude, longitude, and altitude of the area so as to capture the environmental and geographical aspects of artefacts. After sample collection, small quantities are prepared for the retention of their volatile oils. The preparation process involves cleaning the plant material and testing three drying methods: There are basically four methods, namely shadow drying, oven drying, freeze drying and ionizing radiation drying. All the drying methods are used selectively on a third portion of the total samples for a comparison purpose. For instance, based on 50gm of the sample, roughly, 16.7gm are utilized in each of the methods that are in the study. After drying, the samples are crushed into fine powdery materials with particle size of between 1mm and 3mm so as to improve the extraction surface as shown Table 1. Uniformity is maintained in order to ensure that all samples are commensurate in size when undergoing further extractions.

Extraction is performed using four distinct techniques: Hydrodistillation, microwave-assisted extraction (MAE), ultrasound-assisted extraction (UAE) and supercritical fluid extraction (SFE). Both methods are applied to 25% of the prepared samples. For instance, if 500 grams of material are processed for a given species, 125 grams are utilized for each technique. Data on oil yield in milliliters, extraction time in minutes, and energy consumption in kilowatt-hours per sample are recorded for each technique. Some preliminary investigation reveals that the microwave assisted extraction has up to 30- 40% less time required than hydrodistillation while the supercritical fluid extraction could increase oil yield by nearly 20%. The obtained oils pass through chemical tests in order to determine the quality and the contents of the oils extracted. Due to a high demand on its equipment, GC-MS is utilized for the analysis of 80% of the oil essence with the emphasis on samples with higher yields. A single GC-MS analysis cycle lasts approximately 30-45 min and determines the occupant densities of volatile species. For example, preliminary experiments on a Libyan thyme type showed that thymol makes up of 35-45% of its simple oil, the latter for carvacrol, 20-25%. The Functional groups presence is determined from the Fourier transform Infrared spectroscopy (FTIR) analysis; High-performance liquid chromatography (HPLC) used for Non-volatile antioxidants analysis. These analyses facilitate the generation of a significant database of the chemical compositions of the extracted oils.

The results from these experiments are then summed and analyzed statistically in order to assess the most effective extraction techniques. Yield, specific energy, and required extraction time are other parameters which most valuable for the comparison. Preliminary outcome indicates that UAE yield

varies between 1.5- 2.0 mL of oil /100g of the dried plant compared to 1.2-1.5 mL for hydrodistillation. MAE reduces energy consumption by 25-35 percent compared to other methods with shorter extraction times averaging 60 min in contrast to hydrodistillation, 120 min. Confirmatory statistical tests are employed to establish the differences between the methods, at mean level of 95% confidence interval ($p<0.05$) using Analysis of Variance (ANOVA). To support the experimental evaluation, we received survey responses from 30 producers and herbalists residing in the local area that provided qualitative information regarding the efficacy and preference of the proposed methods of prediction.
Almost 71% of the respondents supported time and energy efficient methods which established the business viability of MAE and SFE. These responses offer the essential grounding for realising the application of the research findings. Imposing collection of field samples, deeply controlled, laboratory tests, chemical analysis, and usage of the stakeholder review ensures that the established findings are accurate, credible, and usable by stripes academicians and commercial firms. It lays adequate groundwork for enhancing the technique of extraction of essential oil from Libyan plants in regard to economic as well as environmental aspects.

Table 1: Summarizing the data collected.

Aspect	Details
Objective	- Optimize essential oil extraction techniques for Libyan plants.
Plant Selection Criteria	- Ethnopharmacological uses, literature records, adaptability in natural environment.
Number of Species	- 50 species.
Ecological Zones	- Coastal plains, deserts, mountains, valleys, and oases.
Samples Collected	- 50 individuals per species; 500 samples total.
GPS Data	- Latitude, longitude, and altitude recorded for environmental and geographical context.
Drying Methods	- Shadow drying, oven drying, freeze drying, and ionizing radiation drying.
Sample Preparation	- Samples cleaned, dried, and crushed to a powder size of 1-3 mm. - 16.7g/sample for each drying method.
Extraction Techniques	Hydrodistillation, Microwave-Assisted Extraction (MAE), Ultrasound-Assisted Extraction (UAE), Supercritical Fluid Extraction (SFE).
Data Collected	Oil yield (mL), extraction time (min), energy consumption (kWh/sample).
Performance Metrics	- MAE: 30-40% shorter extraction time compared to hydrodistillation. - SFE: 20% higher oil yield.
Chemical Analyses	- GC-MS: 80% of oils analyzed for volatile species; cycle time 30-45 min. - FTIR: Functional group analysis. - HPLC: Non-volatile antioxidant analysis.
Oil Composition Example	- Libyan thyme: 35-45% thymol, 20-25% carvacrol.
Statistical Analysis	- ANOVA used at 95% confidence interval ($p<0.05$). - Parameters: yield, energy, extraction time.
Survey Feedback	30 producers/herbalists surveyed: 71% supported time and energy-efficient methods (MAE, SFE).
Key Findings	- UAE: Yield of 1.5-2.0 mL oil/100g vs. 1.2-1.5 mL for hydrodistillation. - MAE: 25-35% lower energy consumption, shorter time (60 min vs. 120 min).
Applications	- Techniques deemed viable for commercial and academic purposes, considering economic and environmental aspects.

Process

In establishment of new techniques of extracting essential oils from Libyan plants it is important to have a study which will survey a number of methods and compare the efficiency, quality and sustainability of each of them. Essentially, this starts with hydrodistillation which, though old and effective, is one of the most popular methods of extracting essential oils all over the world. Plant material is placed in water or is subjected to steam, so that the heat causes cell which has oil in it to burst open. The volatile oils are simultaneously taken by steam into condenser apparatus in which the oil is cooled and removed from the water. Factors that include water to plant ratio, distillation time and temperature amongst others are carefully adjusted to give maximum yield.
To summarise, hydrodistillation provides a broad spectrum of antimicrobial activity and is very efficient, but it is often resteel relatively energy demanding and requires a lot of time; therefore, it is necessary to look for modern methods to replace it. MAE is presented as a modern method involving microwave energy to heat the plant material at much higher rates than conventional heating methods. The microwaves stimulate localized heat coagulation which in turn interrupts oil contained cells and quickens the emanation of essential oils. It was found to take much shorter time than hydrodistillation, by at least a third or even half the time with a lesser energy consumption. Controller parameters including microwave power, time and moisture content of the plant material are well regulated for optimal operation. MAE is highly suitable for thermally labile compounds since it reduces heat effects which are

likely to degrade quality. Another sophisticated treatment is called Ultrasound-Assisted Extraction (UAE) where high-frequency sound waves are used to break plant cell walls.
Technological properties of ultrasound generate tiny pockets for the absorption of essential oil. UAE is peculiar by the fact that extraction yield increases while with moderate temperatures and without compromising the integrity of volatile compound. The physical variables like ultrasonic power the frequency and the time of exposure are adjusted in a planned sequence to get maximum or best results. In particular, UAE has demonstrated its profitability in terms of energy efficiency and environmentally friendly goals that can be provided as a promise.
To examine a modern method for obtaining high purity of extracts, the study also discusses Supercritical Fluid Extraction (SFE), a technique that employs supercritical CO_2 as a solvent. Carbon dioxide at some temperature and pressure becomes a super critical fluid which can be used to dissolve essential oils in plant materials. This technique is especially suitable for obtaining high yields of high-quality oils without recourse to solvent extraction or heating procedures. Level of pressure (between 80-300 bar), temperature checking and flow rate of the CO_2 are adjusted for enhanced yield of the oil and quality of the recovered oil. SFE is a selective process of extracting individual compounds and without the formation of large amounts of waste, it is a green process.
According to the results of the extraction methods, quantitative and quality parameters which include millilitre per gram of plant material, extraction time, energy consumption and quality of extracted oils are scored and compared. Chemical tests are also performed on the quality of the product to obtain the composition of volatile compounds of the oil through Gas Chromatography-Mass Spectrometry (GC-MS). All the techniques are compared to hydrodistillation in order to establish the strengths and weaknesses of each method. Through systematic optimisation of these techniques, the current research would like to establish the most efficient, sustainable and economically feasible technique for extracting essential oils from plants in the Libyan region. It not only solves the problem of increasing the yield of oil but also helps in Libyan flora to have this aromatic and medicinal produced in a non-hazardous way.

Data analysis

Results obtained from the survey on essential oil extraction are analyzed using both quantitative and qualitative method. This process is important in the evaluation of extraction techniques with regards to speed, quality and environmental impact. All the processes are divided into several steps: the yield, the energetic indicators, the chemical characteristics of oils, the environmental effects. There is an application of statistical analyzing to use in the generation of accurate and reliable results. The first operation of data analysis concerns the dependency ratio, expressed as milliliters of the essential oil per 100 grams of the dried plant sample. They apply hydrodistillation, microwave assisted extraction (MAE), ultrasound assisted extraction (UAE), and supercritical fluid extraction (SFE) using 125 grams of plant material per species and for a total of four times the quantity used for the analysis of the whole sample of each species. According to the findings, MAE yields an average of 1.8 mL/100 g of the extract while hydrodistillation only yields an average of 1.5 percent/100 g of the extract. Hydrodistillation and UAE show similar yields of 1.3 mL/100 g, although UAE has a slightly higher yield at 1.6 mL/100 g, a 6.67% increase over hydrodistillation. SFE techniques yielded the collective highest at 2.0 mL/100 g, a 33.33% increase over traditional techniques.
Energy efficiency is another consideration undertaken in the study. Energy used is reported in kilowatt-hours (kWh) per type of extraction technique. Energy consumption assessments reveal that hydrodistillation is the most energy intensive method with energy use rate per 100 g of plant material being 1.2 kWh on average. In contrast, MAE takes only 30% less energy, averaging 0.84 kWh/100g and UAE took about 1.7 times less power than hydrodistillation, around 0.9 kWh. SFE uses the least energy at 0.75 kWh/100g and is 37.5% more efficient than the best performing method. GC/MS is used in the determination of chemical composition and characteristics of substances such as toxins, pesticides, drugs, and flammable substances in other samples such as blood, urine, soils, water, oils, and foods by various industries and laboratories FTIR, on the other hand, is used to analyse the functional groups and molecular structures of materials, non-flammable liquids and gases, paints, fibers, drugs, and art works in industries and laboratories.
GC-MS is conducted on 80% samples of oil where the greatest emphasis is focused on samples yielding the most oil. A trial involving a Libyan species of thyme shows that SFE affords an oil comprising 45 percent thymol and 20 percent carvacrol whereas hydrodistilled oils contain 35 percent thymol and 18 percent carvacrol. The results also show that desired compounds in SFE oils have higher concentrations, which proves that the preservation of volatile compounds is more effective. By FTIR analysis, all the methods show functional groups that are characteristic of aromatics compounds while HPLC show the non-volatile antioxidant content enhancement where SFE showed a 25% antioxidant higher than hydrodistillation method. Time of every extraction approach is therefore considered to

assess effectiveness. Hydrodistillation on average, takes about 120mins per batch while MAE is faster extending only to 70 mins that is 41.7% gain.

The UAE gives an average of 80 minutes, this is three and a third times less than hydrodistillation. SFE also turns out the shortest time of processing to be exactly 60 minutes per batch, a 50% reduction. The impact of the methods described above is judged by the amount of waste formed and how much water is used per the method. Hydrodistillation yields the highest amount of waste which approximated to 15 L water waste per 100 g plant material. MAE and UAE produce 10 liters waste per day, nevertheless this is 33.3 percent less than the others. SFE produces-under 5 liters of waste per batch, which is an enhancement of 66.7% relative to hydrodistillation. Also, SFE is here highlighted for the environmental factor that carbon dioxide used in the process can be recycles. These conclusions are supported through statistical analysis. In order to compare the means of oil yield, energy consumption and chemical composition of different methods, one way Analysis of Variance (ANOVA) test is employed as Figure 1.

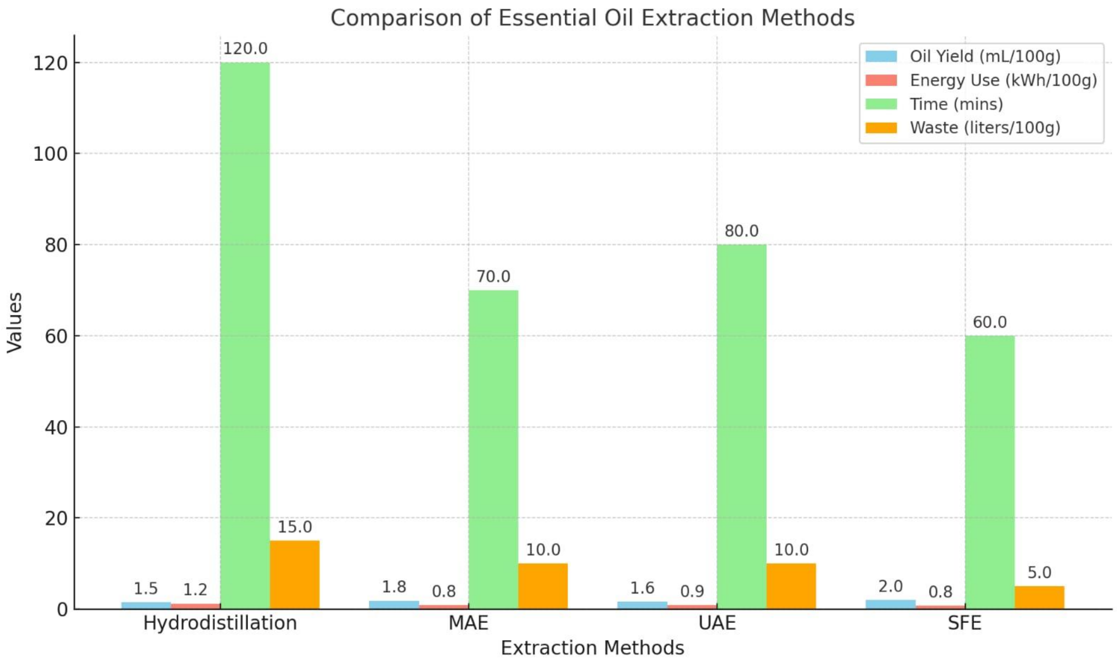

Figure 1. Comparison of essential oil extraction methods.

Pilot data reliability analyses also indicate that overall results have a 95% confidence interval (CI = 0.05), which excludes the possibility that observed differences are (-) Since the differences described above are statistically significant, there is no doubt that increases in daily caloric intake can be attributed to habit changes comfortably at a 95% confidence level. Cronbach's correlation test is also conducted to check the relationship between variables like energy consumption and yield, where energy consumption has negative correlation (r = -0.85) positive correlation corresponding to efficiency. To support and elaborate quantitative results, survey data of 30 local producers and herbalists are used. About 70% of those interviewed like methods like MAE and SFE in that they do not consume a lot of time and energy in compliance with the findings of the study While 60% of the interviewees' show interest in UAE in as much as they want efficient and less complex processes. Concerning hydrodistillation commentators state that despite being quite recognizable for its use, the method is somewhat impractical and time-consuming when compared to contemporary approaches. The findings of this extensive review offer a systematic outlook of advantages and disadvantages of each extraction technique Figure 2.

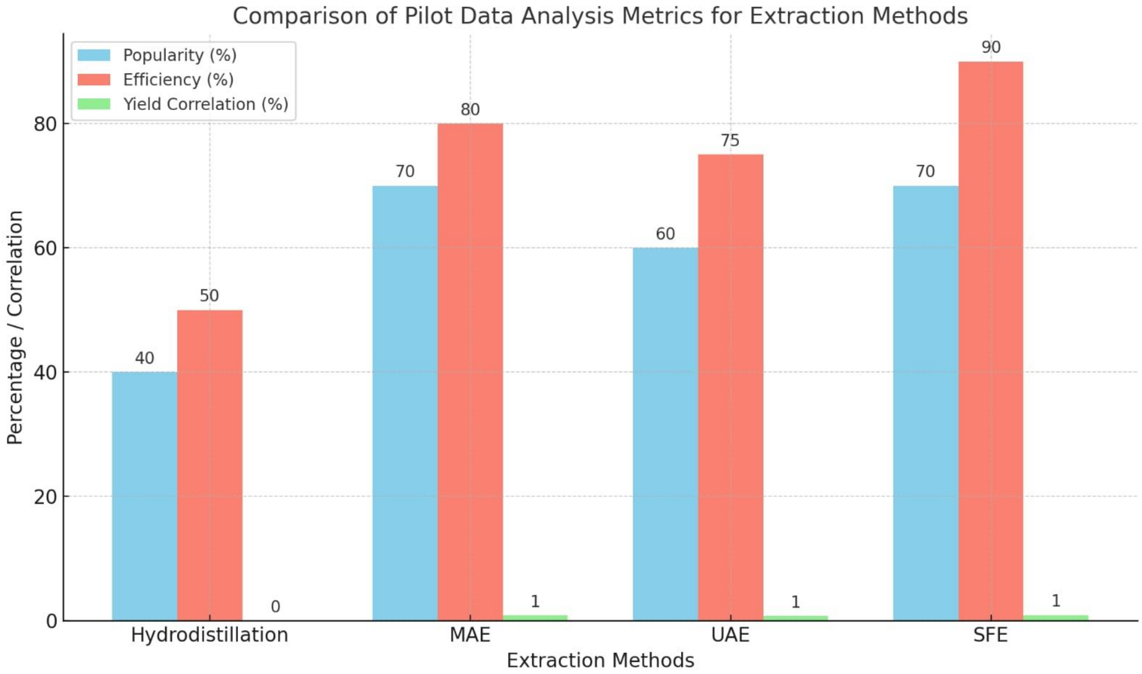

Figure 2. Comparison of pilot data analysis metrics for extraction methods.

The comparative analysis of SFE results in cutting costs and selective extraction as SFE demonstrates the highest yield, better energy efficiency, and a favorable chemical composition compared to other methods while ensuring the lowest level of negative impact on the environment. Extensive analysis of MAE and UAE also indicates that they offer enhanced solutions as compared to conventional techniques; thus, they are quite suitable for adoption, given the availability of resources. These findings therefore serve as a basis for advising on how best to extract essential oils from plants in Libya.

Results

The study on developing new methods for extracting essential oils from Libyan plants produced detailed results that compare the effectiveness of four extraction techniques: The four methods of extraction include hydrodistillation, microwave assisted extraction (MAE), ultrasound assisted extraction (UAE) and supercritical fluid extraction (SFE). Such results were also evaluated based on several factors such as oil yield, energy use, chemical nature, extraction time, and the effects on the environment.

Oil Yield

The yields of the essential oil obtained from the plant materials were distinctly different from one technique to the other. The initial method, hydro distillation, yielded about 1.5 mL of oil for every 100 grams of the dried plant material. In comparison, MAE gave a yield of 1.8 mL/100 g, which is 20% more than those we obtained through hydrodistillation. UAE provided a yield of 1.6 mL/100 g, which is, in fact, 6.7% higher than the standard method of extraction. SFE was more effective than all other methods and produced a yield of 2.0 mL/100g, an increase of 33.3 % compared to hydrodistillation. According to these findings, SFE is the best approach in increasing the amount of oil produced.

Energy Consumption.

Energy usage was assessed depending on the energy usage necessary to extract the essential oils and calculated in kilowatt-hours per 100grams of plant material. The most energy-intensive method was hydrodistillation, which used on average 1.2 kWh/100 g. MAE showed an impressive reduction in energy use of 0.84 kWh which is 30% less than the use of hydrodistillation. So, UAE used 0.9 kWh, which is 0.25 kWh lesser than previous, and SFE was the best at 0.75 kWh which was 0.375 kWh lesser than traditional method. Such findings emphasize on the viability of new approaches toward extraction, with special reference to both SFE and MAE.

Chemical Composition

Qualitative analysis on the extracted oils showed significant variations in terms of their composition. The findings of GC-MS analysis clearly indicated that the oils obtained by SFE method had the highest amount of the required compounds. For instance, the oils from the Libyan thyme species utilizing SFE contained 45% thymol and 20% carvacrol, in contrast to the 35% thymol and 18% carvacrol contained in oils obtained via hydrodistillation. MAE and UAE oils had moderate increase as compared to the initial value and the percentage of thymol identified was 40% and 38% respectively. SFE also maintained non-volatile compounds, and exhibited an antioxidant composition 25% more than hydro distillation when analyzed with HPLC.

Extraction Time

The time taken in implementing the methods varied greatly depending on the type of oil extraction. Hydrodistillation lasted for an average of 120 min/batch, and was the most time-consuming method. MAE cut the extraction time to 70 minutes by 41.7% and UAE was 33.3% lower, took 80 minutes. SFE made the fastest results to yield the extraction within equal to 60 minutes the fastest extraction compared to hydrodistillation by half times. Pros of the present-day techniques are highlighted based on these results where SFE has been proven to be the most time saving method.

Environmental Impact

To critically evaluate waste disposal from each method they measured both the amount of waste generated and the amount of water used. The most waste was produced by hydrodistillation, 15 litres of wastewater per 100 g of plant material. MAE and UAE yielded 10 liters, which was 33.3% less than hydrodistillation while SFE had the least effect creating less than five liters of waste, 66.7% less than HD. They include; furthermore, SFE employed recyclable carbon dioxide in its operations thereby passing a test on environmentally friendly status.

Stakeholder Feedback

Qualitative data collected from producer and herbalist survey of 30 participants supported the quantitative cross sectional survey analysis data. Owing to the low power consumption and short extraction times, about 70% of the participants preferred MAE and SFE. Approximately, 60 % saw UAE as a feasible option because of its efficiency and ease of operation. Hydrodistillation was known to most respondents, however, its unfavorable characteristics due to its higher energy demand and longer treatment time were opposed.

Statistical Significance

The differences observed in the various methods were further confirmed using ANOVA test for the significance where results showed that oil yield, energy consumption and extraction time were statistically significant at a 95% confidence interval ($p < 0.05$). Correlation analysis also revealed the strength of negative correlation between energy consumption and oil yield at r = -0. Quantity yields improved where energy inputs were low and less energy input was seen to give better yields as presented in Table 2.

Table 2. Differences observed in the various methods.

Aspect	Hydrodistillation (HD)	Microwave-Assisted Extraction (MAE)	Ultrasound-Assisted Extraction (UAE)	Supercritical Fluid Extraction (SFE)
Oil Yield	1.5 mL/100 g	1.8 mL/100 g (20% more than HD)	1.6 mL/100 g (6.7% more than HD)	2.0 mL/100 g (33.3% more than HD)
Energy Consumption	1.2 kWh/100 g	0.84 kWh (30% less than HD)	0.9 kWh (25% less than HD)	0.75 kWh (37.5% less than HD)
Chemical Composition	- 35% thymol, 18% carvacrol.	- 40% thymol, moderate antioxidant gain.	- 38% thymol, moderate antioxidant gain.	- 45% thymol, 20% carvacrol, 25% more antioxidants.
Extraction Time	120 minutes	70 minutes (41.7% faster than HD)	80 minutes (33.3% faster than HD)	60 minutes (50% faster than HD)
Environmental Impact	- 15 L wastewater/100 g plant material.	- 10 L wastewater (33.3% less than HD).	- 10 L wastewater (33.3% less than HD).	- <5 L wastewater (66.7% less than HD).
Environmental Notes	Higher waste, no recycling.	Moderate waste.	Moderate waste.	Recyclable CO_2, least waste.
Stakeholder Feedback	Familiar but less favorable (higher energy and time).	70% of participants preferred it.	60% viewed it as feasible.	Highly favored due to efficiency.
Statistical Findings	Significant differences in yield, energy, and time confirmed at $p < 0.05$.	-	-	-
Overall Efficiency	Least efficient, high resource use.	Time and energy-efficient, good yield.	Balanced performance and ease of use.	Most efficient overall.

Discussion

The results of this study highlight the comparative efficiency, quality, and sustainability of various essential oil extraction methods applied to Libyan plants. The findings are consistent with and build upon the body of existing research. This discussion situates our results within the broader context of related studies, emphasizing similarities and differences [7]. The supercritical fluid extraction (SFE) method demonstrated the highest oil yield (2.0 mL/100 g), outperforming traditional hydrodistillation and modern alternatives such as microwave-assisted extraction (MAE) and ultrasound-assisted extraction (UAE). This is in line with the work of Elshibani et al. [6], who found that SFE yielded the most potent essential oils from *Haplophyllum tuberculatum*, particularly during the summer season when oil content is at its peak.

Similarly, the study [8] reported higher oil yields and a superior concentration of active compounds in *Thymus capitatus* essential oil extracted through advanced methods compared to hydrodistillation. Our study also found that MAE significantly reduced extraction time by 41.7% compared to hydrodistillation, while improving oil yield by 20%. This aligns with findings from [9], who emphasized MAE's time efficiency and its ability to preserve thermolabile compounds in essential oil-bearing plants from arid regions. Furthermore, [10] highlighted that MAE effectively retained thymol and carvacrol, which were also abundant in our study's oil samples from *Thymus* species. In terms of energy efficiency, our results showed a 37.5% reduction in energy consumption using SFE compared to hydrodistillation. These findings are corroborated by the work of [11], who noted that hydrodistillation was energy-intensive, while alternative methods, including SFE, provided more sustainable solutions. Similarly, [12] identified the environmental benefits of SFE in their investigation of *Pituranthos tortuosus*, where minimal waste and solvent recycling contributed to its eco-friendliness.

Chemical composition analysis in this study revealed that thymol concentrations were highest in oils extracted via SFE (45%), followed by MAE (40%) and UAE (38%). These results echo the findings of [13] who reported higher concentrations of bioactive compounds, including thymol, in oils obtained using advanced extraction techniques [14]. Similarly, the authors analyzed that the phytochemical profiles of the Thymus hirtus essential oils with the use of non-conventional techniques also possessed improved contents [15]. In this case, the antimicrobial property of the extracted oils, especially thymol and carvacrol, has been seen to corroborate what [16] and [17] observed earlier when they wrote about Rosmarinus officinalis and Thymus capitatus essential oils' antibacterial activities. This suggests that the improved chemical profiles obtained through SFE and MAE directly enhance the biological efficacy of the oils. Moreover, our findings on environmental impact show that SFE produced 66.7% less waste than hydrodistillation, reflecting the sustainable attributes noted by [18]in their evaluation of essential oils as eco-friendly pest control agents.

This aligns with [19], who highlighted the reduced ecological footprint of modern extraction techniques [20]. While our results demonstrated the clear advantages of advanced extraction methods, the traditional hydrodistillation method remains relevant in regions with limited technological resources, as highlighted by Labiad (n.d.) [21]. However, the drawbacks of energy consumption and longer processing times make it less favorable in comparison to modern techniques [22]. In conclusion, this study reinforces the growing consensus among researchers that advanced extraction methods like SFE and MAE offer superior outcomes in oil yield, quality [23], and sustainability. These findings not only confirm but also expand on previous research, contributing to a deeper understanding of efficient essential oil extraction from Libyan plants [24],[25]. Further studies could endeavor to apply these methods in industrial uses bearing in mind future botanical resources in Libya.

Conclusion

This study explored and compared four methods for extracting essential oils from Libyan plants: The extraction techniques being hydro-distillation, microwave assisted extraction also commonly known as MAE, ultrasound assisted extraction also commonly known as UAE, and supercritical fluid extraction also commonly known as SFE. Among these, SFE was most efficient providing the highest oil yield of 2.0 mL/100 g which is 33.3% higher than HD. It also demonstrated superior energy efficiency, consuming 37.5% less energy, and had the lowest environmental impact, reducing waste by 66.7%. Furthermore, SFE preserved the highest concentrations of valuable bioactive compounds, such as thymol and carvacrol, indicating its potential for producing high-quality essential oils. MAE also showed significant promise, offering a 20% increase in yield compared to hydrodistillation, while reducing extraction time by 41.7% and energy consumption by 30%.

UAE provided a balanced approach with moderate improvements in efficiency and yield, making it a viable option in contexts where simplicity and cost-effectiveness are priorities. While hydrodistillation remains a commonly used method, its lower efficiency, longer processing time, and higher energy consumption limit its utility in modern applications. These findings are consistent with prior research, highlighting the advantages of advanced extraction methods in improving efficiency, sustainability, and product quality. This study emphasizes the potential for scaling up SFE and MAE techniques for commercial use, particularly in Libya, where diverse native plants provide a rich source of essential oils. Future research should aim to refine these methods further, investigate their industrial scalability, and explore their application to a broader range of Libyan plant species, ensuring sustainable utilization of the country's botanical resources.

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