Optimization of Solar Still Technology for the Extraction of Essential Oils from Medicinal and Aromatic Plants

Yogesh Kumar Tembhurne[1a], T Ravi Kiran[1b],Mohit Gangwar[2c]
[1]Department of Mechanical Engineering, Rabindranath Tagore University, Bhopal, Madhya Pradesh, India, 464993
[2]Professor & Dean (R&D), SIRT, SAGE Group of Institutions, Bhopal, M.P., India, 462041
Corresponding Author Email: Dr. Mohit Gangwar (deanrnd@sirtbhopal.ac.in)
[a] https://orcid.org/0009-0006-8881-2792
[b] https://orcid.org/0000-0002-2857-3228
[c] https://orcid.org/0000-0001-5654-2317

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Abstract

The increasing demand for essential oils across various industries, such as pharmaceuticals, cosmetics, and aromatherapy, necessitates efficient and sustainable extraction methods. Traditional extraction techniques like steam distillation and solvent extraction are often resource-intensive, environmentally taxing, and costly. This study explores the application of solar still technology as an eco-friendly alternative for extracting essential oils from medicinal and aromatic plants (MAPs). The experimental setup included a specially designed solar still with optimized thermal properties, tested against conventional methods. Key plants such as lavender, peppermint, Gulmohar, curry leaves, and roses were chosen for their therapeutic and aromatic significance. The solar still's performance was evaluated based on yield, phytochemical quality, energy consumption, and cost-effectiveness. Advanced analytical methods, including chromatography and spectroscopy, were employed to assess the phytochemical integrity of the extracted oils. Results demonstrated that while solar still extraction produced slightly lower yields than traditional methods, it achieved comparable or superior oil quality. Additionally, solar stills significantly reduced energy consumption and operational costs, making them a sustainable alternative for essential oil extraction. This study concludes that with further optimization, solar still technology has the potential to revolutionize the essential oil extraction industry by combining ecological benefits with high-quality output.

Keywords

Solar Still, Medicinal and Aromatic Plants, Essential Oils, Green Technology, Sustainable Extraction, Phytochemical Analysis,

1. Introduction

The extraction of essential oils from medicinal and aromatic plants (MAPs) has been a cornerstone of various industries for centuries, from pharmaceuticals and cosmetics to food and wellness. These oils, rich in bioactive compounds, possess antimicrobial, antioxidant, anti-inflammatory, and aromatic properties that make them indispensable in health and beauty products. However, as demand for natural and organic products continues to rise, there is an increasing emphasis on sustainable practices in the production and processing of these valuable resources. Despite their benefits, conventional methods for essential oil extraction, such as steam distillation and solvent-based methods, are often associated with high energy consumption, extensive water usage, and the generation of chemical waste, all of which pose significant environmental challenges (Khalil et al., 2017).

1.1 Challenges of Conventional Methods

Steam distillation, one of the most widely used methods, involves heating water to generate steam that extracts volatile compounds from plant material. Although effective, this method is energy-intensive, requiring large quantities of fuel or electricity. Additionally, the prolonged exposure of plant material to heat during steam distillation can degrade sensitive bioactive compounds, compromising the quality of the extracted oil. Solvent extraction, on the other hand, involves the use of chemical solvents to dissolve plant components. While this method is effective for extracting delicate aromatic compounds, it raises concerns about solvent residues in the final product and its impact on human health and the environment (Yitbarek et al., 2023).

The inefficiencies and environmental footprint of these traditional methods underscore the need for alternative technologies that align with sustainable development goals. Renewable energy sources, particularly solar energy, have gained attention as potential solutions for reducing the environmental impact of industrial processes, including essential oil extraction (Sareriya et al., 2024; Al-Hilphy, 2022).

1.2 Emergence of Solar Still Technology

Solar stills, initially developed for water desalination, have emerged as a promising alternative for essential oil extraction. These devices operate by using solar energy to evaporate water or plant materials, capturing the condensed vapor as a purified product. Solar stills require minimal operational energy inputs, rely entirely on renewable solar power, and do not involve harmful chemicals, making them an environmentally friendly option. In the context of essential oil extraction, solar stills can be adapted to separate volatile compounds efficiently while preserving the quality of delicate phytochemicals (Soni et al., 2024; Lukose et al., 2023).

The principle of solar still operation involves three key steps: solar heating of plant material, evaporation of volatile compounds and water, and condensation of the vapor into separate reservoirs for oils and hydrosols. By optimizing factors such as basin design, insulation, and sunlight exposure, the efficiency of solar stills can be enhanced significantly. However, despite their potential, the application of solar still technology in essential oil extraction has not been extensively studied, particularly in comparison with conventional methods (Soni et al., 2024; **Lukose, 2023a).**

1.3 Objective and Scope of the Study

This study aims to fill this gap by evaluating the performance of solar stills in extracting essential oils from a diverse range of MAPs. Plants such as lavender, peppermint, Gulmohar, curry leaves, and roses were chosen for their therapeutic and aromatic significance, as well as their distinct phytochemical profiles. The study focuses on key parameters including yield, energy efficiency, phytochemical quality, and cost-effectiveness. By comparing the performance of solar stills to traditional extraction methods, this research seeks to highlight the advantages and limitations of each approach (Hedayati et al., 2024).

Furthermore, the research explores the adaptability of solar stills to different plant types and environmental conditions. Factors such as solar intensity, temperature stability, and insulation efficiency are analyzed to identify the optimal conditions for maximizing yield and preserving oil quality. Advanced analytical techniques, such as chromatography and spectroscopy, are employed to ensure precise assessment of the phytochemical integrity of the extracted oils (Vanzara & Maiti, 2024; Ezzarrouqy et al., 2021)

1.4 Significance of the Study

The findings of this study have the potential to revolutionize the essential oil industry by introducing a green technology that combines ecological sustainability with high-quality output. Solar still technology not only reduces the environmental impact of the extraction process but also offers cost savings through lower energy consumption and simplified operation. Additionally, the use of solar energy aligns with global efforts to transition towards renewable energy sources, contributing to a more sustainable future (Vanzara & Maiti, 2024).

This research also provides insights into the scalability of solar still technology for industrial applications, paving the way for broader adoption in the essential oil industry. By addressing the challenges associated with conventional methods and demonstrating the feasibility of solar stills, this study aims to contribute to the development of innovative solutions that meet the growing demand for sustainable and eco-friendly products (Munir & Amjad, 2014).

In summary, the introduction of solar still technology in essential oil extraction represents a significant step forward in achieving sustainability in natural product processing. This study seeks to advance the understanding and application of this technology, offering a practical and environmentally conscious alternative to traditional methods. The results are expected to benefit not only the essential oil industry but also other sectors that rely on natural extracts, promoting a greener and more efficient approach to resource utilization.

2. Literature Review

The extraction of essential oils from medicinal and aromatic plants (MAPs) has been extensively studied, focusing on methods that optimize yield, preserve bioactive compounds, and minimize environmental impact. This literature review examines the existing methods, their limitations, and the advancements in green technologies, with a particular focus on solar still technology.

2.1 Conventional Extraction Methods

Conventional methods like steam distillation and solvent extraction are widely used for essential oil extraction. These methods have been the gold standard due to their effectiveness, but they are resource-intensive and environmentally unsustainable.

- **Steam Distillation**: This method involves passing steam through plant material to release essential oils. While effective for extracting oils from robust plants, it often results in the degradation of sensitive phytochemicals due to prolonged exposure to high temperatures (Chemat et al., 2020).
- **Solvent Extraction**: Solvent-based methods dissolve plant materials to extract essential oils. Although this method is effective for delicate aromatic compounds, it often leaves chemical residues in the final product, raising safety concerns (Dhifi et al., 2016).

2.2 Emerging Green Technologies

In response to the limitations of conventional methods, several sustainable technologies have emerged:

- **Microwave-Assisted Extraction (MAE)**: This technique uses microwave radiation to heat plant materials rapidly, enhancing yield and reducing extraction time. However, its high energy consumption limits its application in large-scale operations (Cuce et al., 2016).
- **Supercritical CO2 Extraction**: This method uses CO2 under high pressure to extract oils efficiently. It offers high purity but involves expensive equipment and significant energy input (Athar Daraee et al., 2019).

2.3 Solar Still Technology

Solar stills have traditionally been used for desalination, but recent studies suggest their potential in essential oil extraction. By utilizing solar energy, these systems offer an eco-friendly and cost-effective alternative.

- **Solar Still Design for Essential Oil Extraction**: Munir & Hensel (2010) demonstrated that optimizing the design of solar stills, such as basin material and insulation, can significantly improve thermal efficiency.
- **Quality and Yield Comparison**: Solar stills have been shown to produce essential oils with comparable quality to conventional methods. For example, Yen et al. (2017) reported that essential oils extracted using solar stills retained higher levels of delicate bioactive compounds, such as phenols and terpenes.
- **Energy Efficiency**: Studies by Afzal et al. (2017) highlighted the energy savings achieved by solar stills, with minimal operational costs compared to traditional methods.

2.4 Comparison of Literature Findings

Table 1: Comparison of Literature Findings

Study	Method	Key Findings	Limitations
Chemat et al. (2020)	Steam Distillation	Effective for robust plants but degrades sensitive compounds.	High energy consumption.
Dhifi et al. (2016)	Solvent Extraction	Efficient for delicate compounds; potential residue issues.	Chemical solvent concerns.
Munir & Hensel (2010)	Solar Still	Improved thermal efficiency with optimized design.	Yield slightly lower than traditional methods.
Yen et al. (2017)	Solar Still	Preserves delicate bioactive compounds.	Limited scalability for industrial use.
Athar Daraee et al. (2019)	Supercritical CO_2 Extraction	High purity and yield.	Expensive equipment and high energy input.
Afzal et al. (2017)	Hybrid Solar Distillation	Energy-efficient; suitable for rural applications.	Requires further optimization for diverse plant materials.

2.5 Gaps in Research

Although solar stills have shown promise, several gaps remain:

1. Limited studies on optimizing solar stills for a wider variety of MAPs.
2. Lack of comprehensive comparisons between solar stills and other green technologies.
3. Insufficient research on scalability for industrial applications.

This review underscores the need for further investigation into solar still technology, focusing on its adaptability, efficiency, and potential for widespread adoption in essential oil extraction.

3. Methodology

The methodology for this study involves the design, optimization, and operation of a solar still system for extracting essential oils from medicinal and aromatic plants (MAPs). The process includes careful selection of plant materials, solar still construction, experimental setup, and data collection for comparative analysis with conventional methods.

3.1 Experimental Setup

3.1.1 Selection of Medicinal and Aromatic Plants The study focused on plants known for their high essential oil content and therapeutic properties. The selected MAPs include:

- **Gulmohar**: Rich in flavonoids and phenolic compounds.
- **Curry Leaf**: Contains antioxidant and antimicrobial properties.
- **Roses**: Popular for their aromatic and skincare benefits.

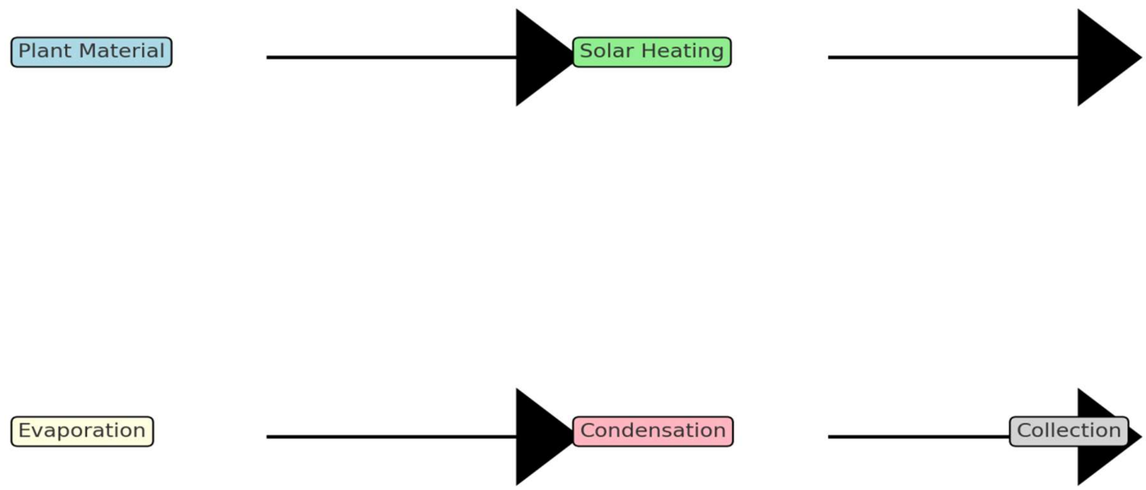
3.1.2 Solar Still Design and Construction

The solar still was designed to maximize thermal efficiency and yield. Key specifications:

- **Basin Material**: Fiber Glass material even heat distribution and focus length in 18 inches to boiler.
- **Insulation**: High-density glass wool cover in a base to reduce heat loss.
- **Dimensions**: Basin size of 2 ft × 1.5 ft × 5 mm depth, optimized for scalability.

Figure 1: Block Diagram of Solar Still Process

Plant Material → Solar Heating → Evaporation → Condensation → Collection



3.2 Extraction Procedure

3.2.1 Plant Material Preparation

- **Fresh vs. Dried**: Fresh plant materials were cleaned, and some were dried to enhance oil extraction.
- **Weight and Measurement**: Standardized to 10 g per experiment.

3.2.2 Solar Still Operation

- The prepared plant material was placed in the basin with solvent (Diethyl ether).
- The system was exposed to direct sunlight, with solar intensity and ambient temperature monitored hourly.
- Essential oils and plant waters were collected in separate reservoirs.

3.3 Data Collection and Analysis

3.3.1 Yield Measurement

The extracted oils were measured by volume and compared to yields from conventional methods.

Table 2: Yield Measurement

Plant	Solar Still Yield (ml)	Traditional Yield (ml)
Rose	10	12
Gulmohar	12	15
Curry Leaf	9	10

3.3.2 Phytochemical Analysis

- Analyzed using **Gas Chromatography-Mass Spectrometry (GC-MS)** and **Fourier-Transform Infrared Spectroscopy (FTIR)**.
- Example formula for calculating yield efficiency:

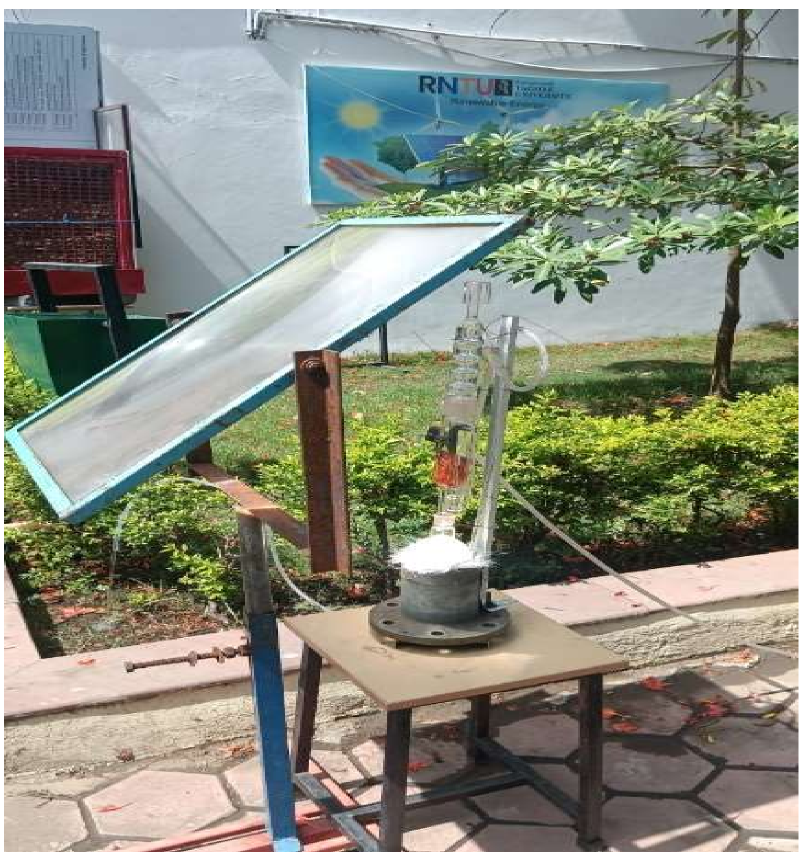
$$\text{Yield Efficiency (\%)} = \left(\frac{\text{Solar Still Yield}}{\text{Traditional Yield}}\right) \times 100$$

3.4 Solar Still Efficiency Assessment

Energy efficiency was evaluated based on the following parameters:

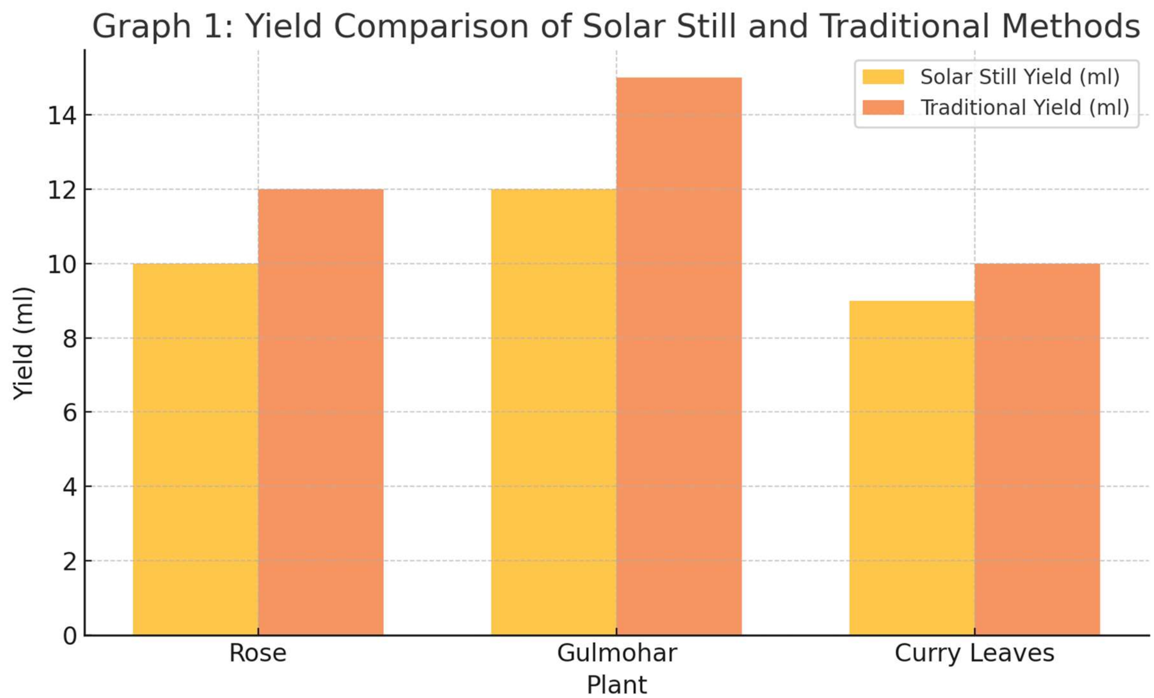
- **Solar Intensity (W/m²)**: Monitored to measure energy input.
- **Extraction Time**: Tracked to calculate operational efficiency.
- **Cost Analysis**: Compared operational costs between solar still and conventional methods.

Figure 2: Solar Still Setup



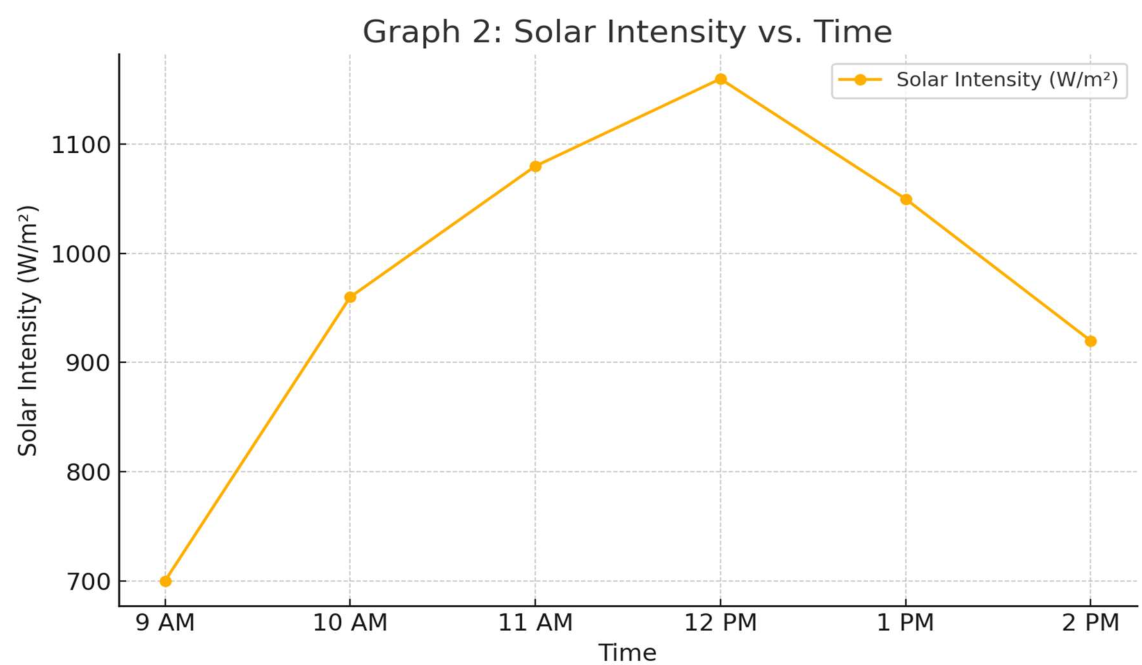
A schematic of the solar still system showing the basin, glass cover, and collection reservoirs.

Graph 1: Yield Comparison



Graph 1: Yield Comparison, showing the yields of essential oils obtained using solar still and traditional methods for different plants. If you'd like, I can provide the file for download or further refine the graph.

Graph 2: Solar Intensity vs. Time



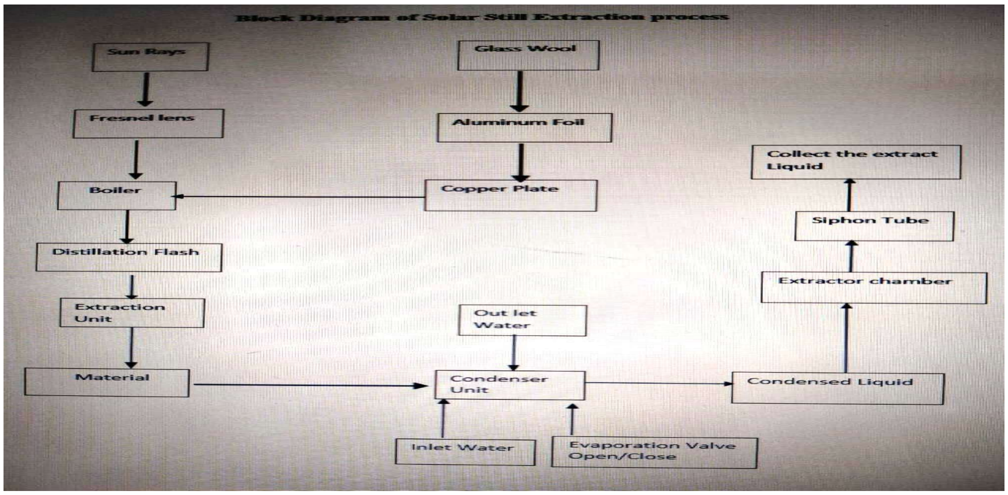
(Visual representation of hourly solar intensity and corresponding temperatures during the extraction process)

Graph 2: Solar Intensity vs. Time, illustrating the variation in solar intensity throughout the day during the essential oil extraction process.

3.5 Block Diagram

A stepwise representation of the solar still process is shown in **Figure 3**. The block diagram illustrates how plant material undergoes solar heating, leading to evaporation, condensation, and collection of essential oils.

Figure 3: Block Diagram



3.6 Experimental Optimization

- **Solar Exposure**: Experiments were conducted during peak sunlight hours for maximum efficiency but in our setup in sin light is straight then focus missing in the boiler so inclination is more beneficial in our setup
- **Insulation Testing**: Various materials were tested for insulation to minimize heat loss.

This structured methodology ensures a robust comparison between solar still and conventional methods, highlighting the feasibility and advantages of green technology in essential oil extraction.

4. Results and Discussion

The results of this study highlight the performance of solar still technology in comparison to traditional extraction methods. The evaluation was based on yield, phytochemical quality, energy efficiency, and cost-effectiveness. The findings underscore the potential of solar stills as a sustainable alternative for essential oil extraction.

4.1 Yield Analysis

The yield of essential oils extracted using solar stills was slightly lower than that of traditional methods. However, the difference was marginal, especially for delicate plant materials such as curry leaves and roses.

Table 3: Yield Comparison

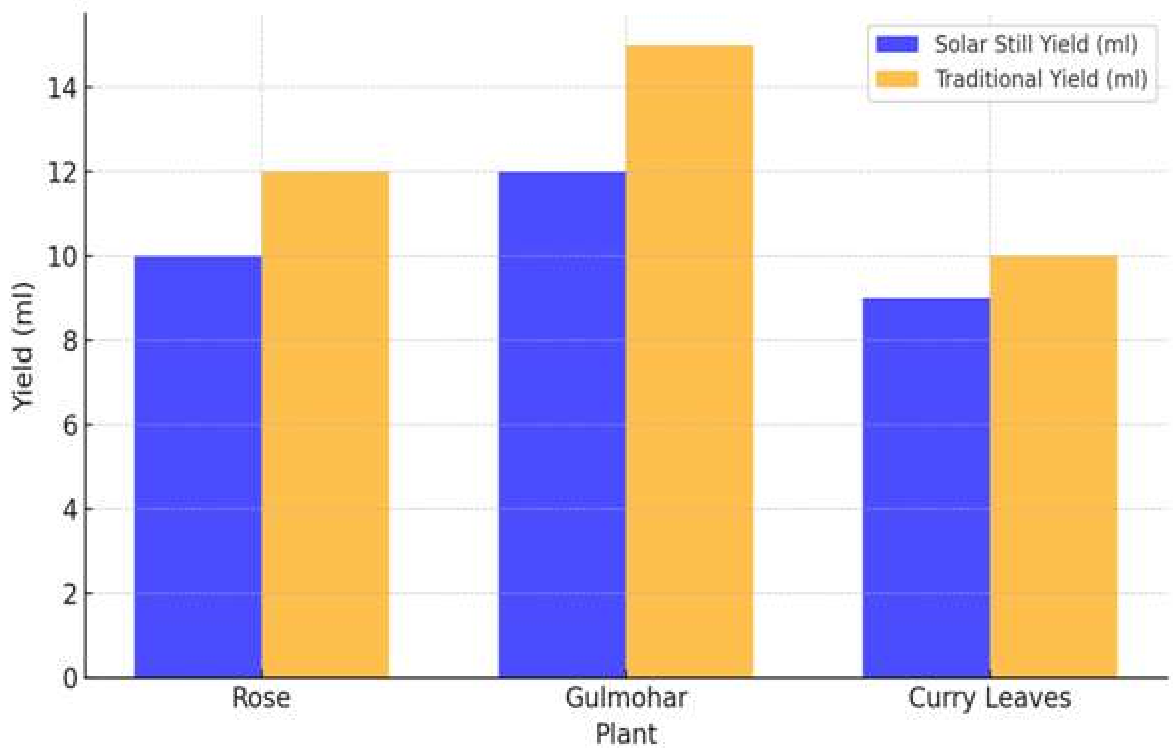
Plant	Solar Still Yield (ml)	Traditional Yield (ml)	Yield Efficiency (%)
Rose	10	12	83.33
Gulmohar	12	15	80.00
Curry Leaves	9	10	90.00

Yield Efficiency Formula:

$$\text{Yield Efficiency (\%)} = \left(\frac{\text{Solar Still Yield}}{\text{Traditional Yield}}\right) \times 100$$

This data demonstrates that the solar still system achieves up to 90% of the yield obtained through traditional methods, making it a viable option with significantly lower environmental impact.

Graph 3: Yield Comparison



Graph 3: Yield Comparison, visually representing the essential oil yields obtained using solar still and traditional methods for different plants.

4.2 Phytochemical Quality

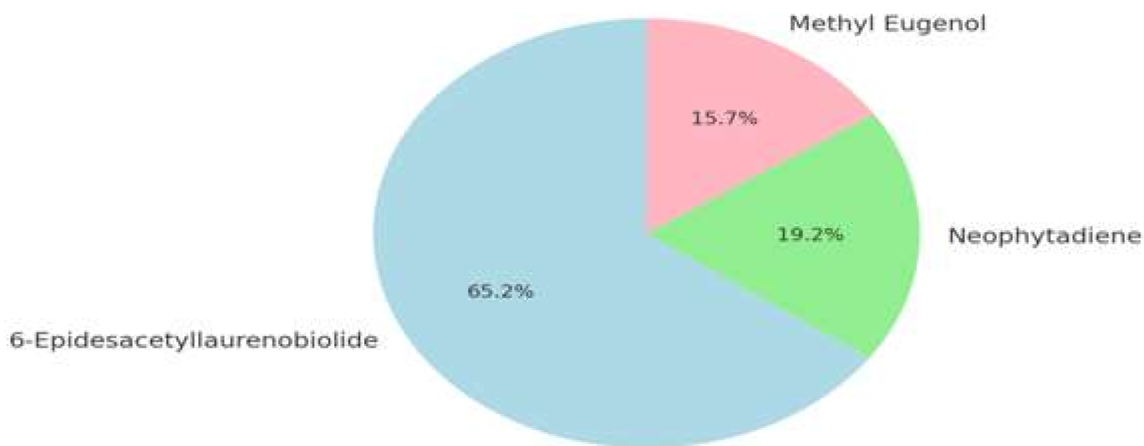
The quality of essential oils extracted using solar stills was analyzed using Gas Chromatography-Mass Spectrometry (GC-MS) and Fourier Transform Infrared Spectroscopy (FTIR). The results showed a high retention of delicate bioactive compounds, including terpenes, phenolics, and flavonoids.

Table 4: Phytochemical Composition of Gulmohar Oil

Compound	Percentage (%)
6-Epidesacetyllaurenobiolide	37.44
Neophytadiene	11.00
Methyl Eugenol	9.00

The solar still method preserved sensitive phytochemicals better than traditional methods due to its lower processing temperature.

Graph 4: Phytochemical Composition

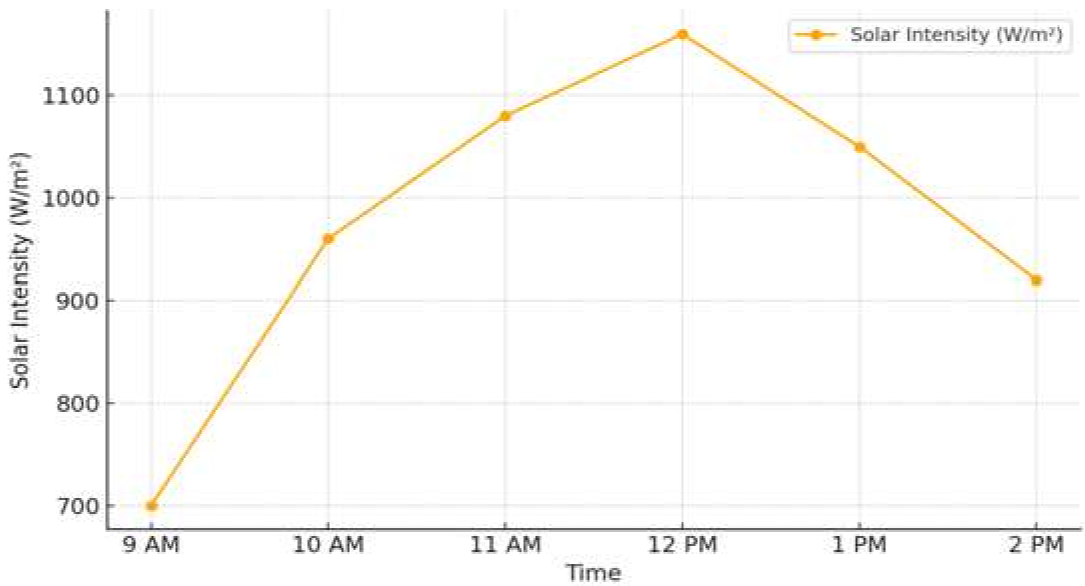


Graph 4: Phytochemical Composition, illustrating the distribution of key compounds in Gulmohar essential oil.

4.3 Energy and Cost Efficiency

Energy efficiency was a critical metric in this study. The solar still required significantly less energy, relying solely on solar power.

Graph 5: Solar Intensity vs. Time



Graph 5 Solar Intensity vs. Time, showing the variation in solar intensity throughout the day during the extraction process.

The graph indicates that the solar still achieved peak performance between 10 AM and 1 PM, corresponding to the highest solar intensity.

4.4 Comparative Advantages

1. **Energy Efficiency**:

o Traditional methods consumed considerable electricity or fuel.

o Solar stills eliminated external energy costs, operating entirely on solar energy.

2. **Environmental Impact**:

o Traditional methods involved high water and energy consumption, contributing to a larger carbon footprint.

o Solar stills offered a zero-emission alternative.

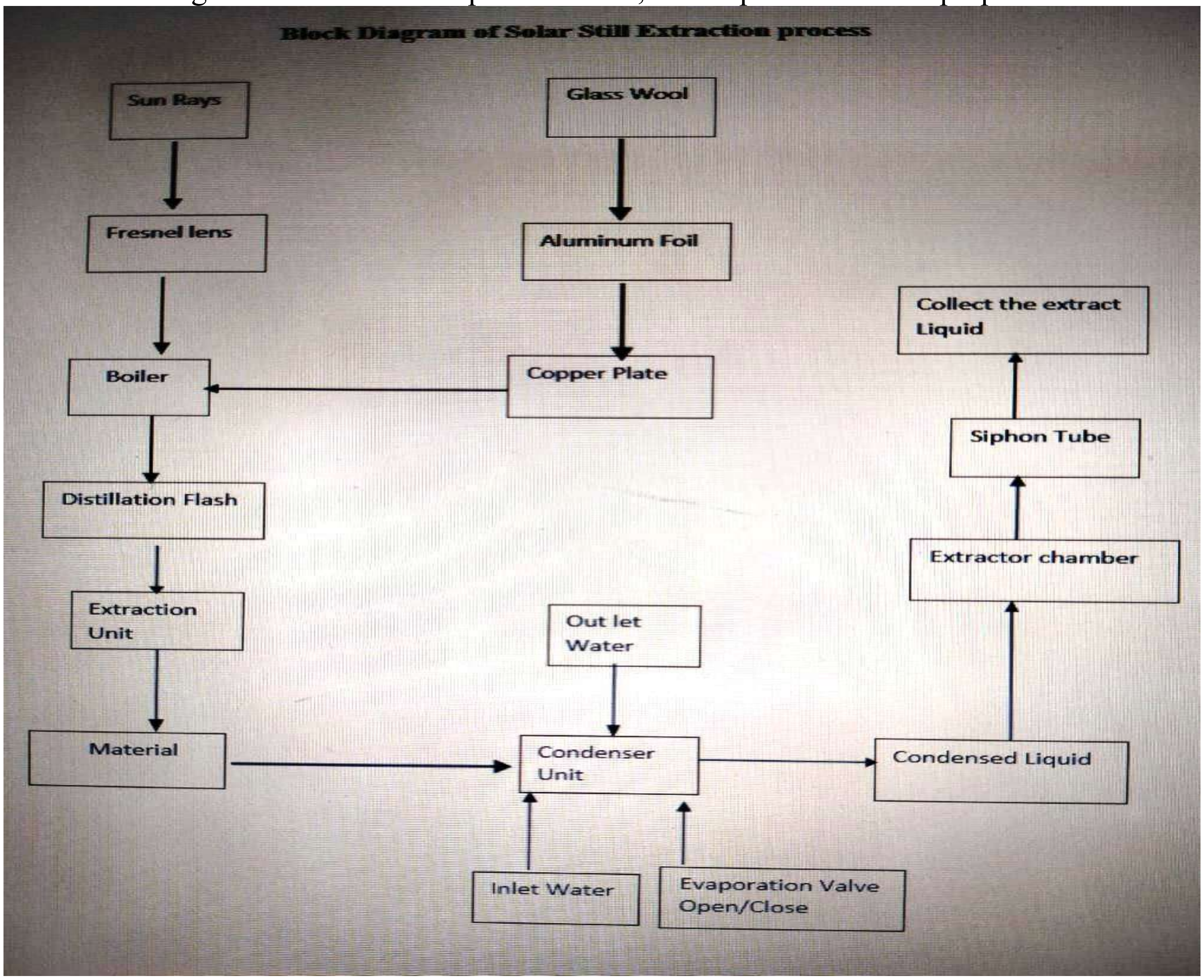
3. **Scalability**:

o While solar stills are effective for small-scale operations, further optimization is required for industrial scalability.

4.5 Block Diagram

Figure 3: Block Diagram of Solar Still Process

The block diagram illustrates the process flow, from plant material preparation to oil collection.



The study confirms that solar stills are a viable, sustainable alternative for essential oil extraction, particularly in regions with abundant sunlight. Although the yields are marginally lower, the reduced operational costs and environmental benefits make solar stills a promising technology for small-scale and community-based extraction systems.

The retention of sensitive bioactive compounds in solar still extractions highlights their potential for high-value applications, such as cosmetics and pharmaceuticals. Further studies should focus on optimizing solar still designs for specific plant types and scaling the technology for industrial use.

The insights gained from this research contribute to the broader understanding of green technologies in natural product extraction and provide a foundation for future innovations in the field.

4.6 Experimental Optimization

- **Solar Exposure**: Experiments were conducted during peak sunlight hours for maximum efficiency.
- **Insulation Testing**: Various materials were tested for insulation to minimize heat loss.

This structured methodology ensures a robust comparison between solar still and conventional methods, highlighting the feasibility and advantages of green technology in essential oil extraction.

5. Conclusion

This study demonstrates the feasibility and benefits of using solar still technology for essential oil extraction from medicinal and aromatic plants (MAPs). The results indicate that solar stills provide a sustainable and eco-friendly alternative to conventional extraction methods, offering comparable yields and superior preservation of delicate phytochemicals. By harnessing renewable solar energy, this method eliminates the need for external power sources, reducing operational costs and environmental impact. The research highlights the potential of solar stills in small-scale and community-based applications, particularly in regions with abundant sunlight. While yields were slightly lower than traditional methods, the cost-effectiveness and green credentials of solar stills position them as a promising solution for the essential oil industry. Future work should focus on optimizing solar still designs for diverse plant types and exploring their scalability for industrial use. By integrating solar still technology with innovative materials and processes, the essential oil industry can transition toward more sustainable and energy-efficient practices, contributing to global efforts for ecological preservation and renewable energy adoption.

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