Optimization of Essential Oil Extraction Using Pomelo Peels as the Raw Material: A Process Study

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ABSTRACT

Essential oils are natural extracts known for their versatility, capturing widespread interest due to their diverse applications and the increasing consumer preference for safe and efficient health solutions. Their inherent natural properties make them valuable in various industries, including food, pharmaceuticals, agriculture, and textiles. In that respect, this research focuses on optimizing essential oil extraction using waste pomelo peels as the raw material. There two extraction methods, water distillation and Soxhlet, were employed to investigate the feasibility of utilizing pomelo peels for essential oil extraction. The main objectives that were meant to be achieved in this research included comparing the efficiency of water distillation and Soxhlet extraction methods, optimizing the essential oil extraction process by adjusting vital physical parameters, and determining the most effective pomelo peels. The waste pomelo peels required for oil extraction were collected around the Colombo district (Sri Lanka). Two distillation setups were used for water distillation: industrial-scale water distillation and lab-scale water distillation apparatus. The investigations revealed that Fresh-Grind pomelo peels exhibited notably higher efficiency for water distillation, with a yield of 0.8%. There the oil extraction yield for the industrial and laboratory extraction setup was reported as 0.5% and 0.8%, respectively. The Soxhlet experiments were conducted using various solvents: toluene, acetone, n-hexane, methanol and acetonitrile. However, based on the experiment results, n-hexane emerged as the most effective, yielding an efficiency of 7.1%. So, the Soxhlet extraction method was selected to optimize the process followed in essential oil extraction by waste pomelo peels.

KEYWORDS: *Essential oil extraction, Optimization, Soxhlet method, Waste pomelo peels, Water distillation*

1 INTRODUCTION

Essential oils, also known as volatile odoriferous oils, are aromatic oily liquids extracted from various parts of plants, including leaves, peels, bark, flowers, buds, seeds, and more. Several methods, such as steam distillation and expression, can extract these oils from plant materials. Steam distillation has been widely utilized among these methods, particularly in commercial-scale production (Cassel & Vargas, 2006; Di Leo Lira et al., 2009). Essential oils, prevalent in various plants, particularly aromatic ones, exhibit diverse odours and flavours influenced by the types and quantities of constituents within the oils. The amount of essential oil extracted from different plants varies, impacting the overall cost of the essential oil (Tongnuanchan & Benjakul, 2014). Various plants harbour essential oils, with distinct plant parts serving as primary sources of these oils. These encompass roots, peels, leaves, seeds, fruits, bark, and more. Essential oils derived from plants typically constitute intricate natural compound mixtures containing polar and nonpolar elements. The diversity of plant materials and their elemental oil compositions contributes to the complexity and richness of these natural extracts (Masango, 2005).

Essential oils, known for their aromatic properties, can be extracted from different parts of the plants using various methods. The choice of extraction method depends on the specific botanical material, its state, and its form. The extraction process dramatically influences the quality of essential oils, making it a critical factor in preserving their chemical signature and natural characteristics. Inappropriate procedures may result in damage or alteration, leading to a loss in bioactivity and undesirable changes such as discolouration, off-odour/flavour, or increased viscosity (Tongnuanchan & Benjakul, 2014). Using appropriate extraction techniques is crucial to prevent alterations and preserve the integrity of the extracted essential oil. Various methods are available for extracting essential oils:

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Steam distillation, Hydrodiffusion, Water distillation, Cold press extraction, Enfleurage, Solvent extraction, and CO_2 extraction.

The market features various popular essential oils (Essential Oil Market, 2022). Citrus Essential Oils: Lemon, Orange, Grapefruit, Lime. Floral Essential Oils: Lavender, Rose, Ylang-Ylang, Jasmine. Herbaceous Essential Oils: Chamomile, Rosemary, Parsley, Tea Tree, Oregano. Minty Essential Oils: Spearmint. Spicy Essential Oils: Various spices with exotic aromas. Musky Essential Oils: Frankincense. Earthy Essential Oils: Pine, Sandalwood, Cypress. Camphoraceous Essential Oils: Camphor, Cajeput, Eucalyptus.

Traditionally embraced by natural medicine practitioners, essential oils are now experiencing a surge in demand beyond this demographic (Essential oil market, 2022). In 2020, the market reached a value of 8.74 billion USD, with a projected compound annual growth rate of 7.5% until 2027. The heightened demand is fueled by factors such as the amplified health consciousness following the COVID-19 pandemic, a substantial uptick in aromatherapy interest within the broader context of alternative medicine, and a growing preference for organic, sustainable products among consumers (Stoelzle Glass Group, 2022). The essential oils market is witnessing a surge in demand, notably driven by the pervasive popularity of citrus oils. Citrus oils dominate the market landscape, including invigorating varieties like orange, lemon, and bergamot. Renowned for their refreshing scents, these oils are used extensively in perfumes, candles, and air fresheners, contributing to uplifting and vibrant environments (Essential Oil Market, 2022).

Essential oils, being highly volatile, are susceptible to damage from oxygen and light. Optimal preservation involves airtight sealing, UV protection, and storage in excellent, dry conditions. Amber glass is an ideal packaging material, offering light-filtering properties that shield sensitive oils from harmful UV rays. Moreover, glass, whether amber or white, ensures no interaction with the product, preventing the release of material particles and preserving essential oil purity—a crucial quality standard. Glass packaging not only sustains product integrity but also aligns with sustainability goals, being recyclable and contributing to responsible environmental practices.

Due to its high water content (77% to 80% DB), pomelo peel is prone to quick spoilage, making long-term storage challenging. While dehydration methods can remove moisture for extended storage, the economic feasibility of large-scale drying processes is hindered by high associated costs (Rahman et al., 2016 & Jung et al., 2014). Due to the absence of cost-effective methods for utilizing pomelo peel, standard disposal practices involve landfill disposal and burning (Zhu et al., 2017). In pomelo-growing countries like China, Thailand, the Philippines, and Malaysia, the landfill disposal of substantial quantities of pomelo peel could have adverse environmental consequences. Burning and landfilling agricultural and food waste typically generate greenhouse gases (CO_2 and CH_4), contributing to environmental pollution (Santiago-De la Rosa et al., 2017 & Tonini et al., 2018).

The successful cultivation of pomelo trees is contingent on accommodating climate and soil conditions. Pomelo trees exhibit adaptability to a diverse range of soil types as long as the soil is adequately deep, well-drained, and possesses good aeration while retaining sufficient moisture. Maintaining an optimal pH level within the range of 5.5 to 6.5 is crucial for the health of pomelo trees. It is advised to avoid saturated soils, sticky, heavy soils, and those with a hardpan layer. Pomelo thrives in lowland tropics at elevations up to 400 m above sea level, where the temperatures ideally range from 23 to 30 °C. Additionally, annual rainfall of 1,500 to 1,800 mm is essential to support the robust growth of pomelo trees.

The essential oils extracted from pomelo peels have significant applications across various industries due to their rich aroma-active volatiles and are generally recognized as safe (GRAS). These citrus essential oils are widely utilized in the cosmetic, flavour, beverage, and pharmaceutical industries. Beyond their aromatic properties, citrus Essential oils, including those from pomelo peels, are widely known to contain bioactive compounds known for their anti-oxidation and antimicrobial properties. The recovery of essential oils from citrus fruit processing by-products, such as pomelo peels, has garnered substantial research attention (Tocmo et al., 2020). The chemical composition of pomelo peel essential oils is characterized by a diverse array of volatile compounds, including terpenoids, aldehydes, aliphatic alcohols, esters, ketones, and acids. Limonene consistently emerges as the most dominant compound, with other significant constituents contributing to the unique sensory profiles of pomelo peel essential oils. The concentrations and diversity of volatile components in pomelo peel essential oils vary across pomelo cultivars, influenced by genetic and geographical differences, growing practices, and extraction methods. Studies emphasize the need to evaluate the impact of odorant compounds, considering factors such as aroma threshold, extraction method, and varietal differences, to comprehend better the overall aroma profile of pomelo peel essential oils.

In 2024, the market for pomelo peels essential oil is thriving, with a 5ml bottle of 100% pure pomelo peels essential oil priced at an affordable 2 USD (Alibaba, 2024). This competitive pricing reflects the accessibility of this sought-after essential oil, making it an attractive option for consumers seeking the unique and aromatic benefits of pomelo peels.

Alternatively, pomelo peel has been explored as a raw material for the fabrication of low-cost, functional materials, including adsorbents (Chai et al., 2015; Zhu et al., 2017), active carbons (Foo & Hameed, 2011; Li et al., 2016; Nowicki et al., 2016), and animal feeds (Zema et al., 2018). While these alternative uses of pomelo peel waste hold promise for mitigating its potential adverse environmental impact, there are concerns about the high production costs, notably the energy-intensive processes involved, which may result in only marginally profitable products. Researchers have investigated alternative approaches to recover value-added products, including pectin, essential oils, and functional food ingredients, in pursuing economically feasible and efficient means to utilize pomelo peel waste.

While prior investigations, such as Giang (2020), were predominantly focused on the water distillation method for extracting essential oil from pomelo peels, this research distinguished itself by the introduction of both industrial-scale and lab-scale water distillation units, alongside the innovative use of Soxhlet extraction. This approach optimized the extraction process and emphasized the uniqueness of Soxhlet extraction for waste pomelo peels for the first time, contributing valuable insights to the field. Moreover, significant efficiencies and unique oil compositions were revealed in the findings, highlighting the potential for enhanced essential oil production specific to Sri Lankan pomelo varieties, setting this study apart from existing literature.

This investigation not only evaluates the effectiveness of these extraction methods but also delves into the associated cost and energy consumption involved in oil production. By adopting a comprehensive approach, the study aims to assess these extraction techniques' environmental and economic viability. A significant aspect of this study involves conducting a life cycle assessment (LCA), which was overlooked in earlier research on pomelo peels. This aspect provides crucial insights into the environmental impact of the extraction process for waste pomelo peels, thus contributing to the holistic understanding of the extraction process.

2 MATERIALS AND METHODS

2.1 Collection and Preparation of Raw Materials

The collection and preparation of raw materials began with gathering waste pomelo peels from various regions in Sri Lanka, including Elpitiya, Balangoda, and Kurunagala. Subsequently, the waste pomelo peels are cleaned and cut into small pieces measuring 1×1 cm2. All pieces were stored in a freezer at 4 degrees Celsius after cutting. A small quantity of the 1×1 cm2 -sized pieces underwent drying in the oven at 45 degrees Celsius. After, they stocked in the dry locker. Before some experiments, these dried and fresh pomelo peels were grinded using a grinder.

2.2 Extraction of Waste Pomelo Peels

Waste pomelo peels were extracted using various methods, including water distillation and soxhlet extraction techniques. The study employed three setups: a lab-scale water distillation apparatus, an industrial-scale water distillation unit, and a soxhlet extraction apparatus. The yield of waste pomelo peel oil (Y) obtained for all samples was calculated by,

$$\text{Y (\%)} = \frac{Volume\ of\ essential\ oil\ (ml)}{Amount\ of\ raw\ materials\ (g)}\ 100\% \qquad (1)$$

In the lab-scale water distillation apparatus, the extraction process involved using four pomelo peels: Dry – 1×1 cm², Dry - Grind, Fresh – 1×1 cm², and Fresh - Grind. Each type was subjected to the lab-scale water distillation apparatus with 100g of peels placed in a 500 mL round-bottom flask containing 500 mL tap water, a ratio of waste pomelo peels to water at 1:5. The device was then powered on, and the temperature was set to 120°C. Essential oil extraction was conducted for 2 hours. The resulting mixture of water and oil was evaporated and collected in a beaker. This mixture and 25ml hexane were added to a 500ml separation panel. After allowing the mixture to sit for one hour for separation, the oil and hexane were separated. The hexane evaporated, and the collected essential oil was stored in amber glass bottles.

In the industrial-scale water distillation unit, the extraction process focused on utilizing fresh-grind pomelo peels. A total of 6 kg of peels were placed in a 70 L distilling vessel along with 30 L of tap water, a ratio of waste pomelo peels to water at 1:5. The industrial-scale water distillation unit was powered on, initiating the distillation process. Heater activation and adjustment of condenser temperature settings to 120°C and 25°C were performed. Essential oils were then extracted from the waste pomelo peels, mixing water and oil. Following collection, distinct layers of oil and water were observed. Subsequently, 50 ml of n-hexane was added to a 1-litre separation panel containing the water-oil mixture. After mixing and allowing the mixture to sit for one hour, the oil and n-hexane mixture was separated. A water distillation apparatus evaporated hexane from the mixture, and the extracted essential oils were carefully stored in amber glass bottles.

The extraction process utilized Acetone as the solvent in the soxhlet extraction apparatus. A thimble containing 100g of pomelo peel was placed in the apparatus. In contrast, 300 ml of Acetone was placed in a 500 mL round-bottom flask, including a 1:3 ratio of pomelo peels to solvent. The device was powered on, and the temperature was adjusted to match the boiling point of Acetone (56.5°C). The extraction time, set at 10 hours, was determined based on solvent yield visualization. The resulting output was a solvent-oil mixture, which was collected. Subsequently, a water distillation apparatus evaporated the solvent from the mixture. The extracted essential oil was collected and carefully stored in amber glass bottles.

2.3 Solvent Evaporation Process

The Solvent Evaporation Process, implemented across all three setups, employed a water distillation apparatus. This technique facilitated the recovery of all solvents, ensuring minimal potential impact on human health and the environment. The procedure included placing the solvent-oil mixture in a 500 mL round-bottom flask connected to a lab-scale water distillation apparatus, which was then powered on. The temperature was adjusted to align with the boiling point of each solvent and monitored by a thermometer. Subsequently, the solvent underwent evaporation, and the evaporated solvent was collected. The remaining oils in the flask were gathered, and the collected oils were stored in amber glass bottles.

2.4 Process optimization

In the initial process optimization phase, various solvents were tested for their effectiveness in extracting waste pomelo peels. The solvents, including Toluene, Acetone, Methanol, n-hexane, and Acetonitrile, were evaluated based on specific physical parameters such as boiling point, extraction time, and pomelo peels to solvent ratio. For instance, n-Hexane, with a boiling point of 68.7°C, was used at a ratio of 1:3 (pomelo peels to solvent) with an extraction time of 7 hours, utilizing 100g of pomelo peels and 300ml of solvent. After conducting experiments, the results were meticulously analyzed to determine the most efficient solvent for the extraction process.

In the subsequent phase of the process optimization, different ratios of pomelo peels to solvent were investigated, focusing specifically on n-hexane as the solvent. The ratios tested ranged from 1:2 to 1:4, with corresponding volumes of pomelo peels and n-hexane utilized. For instance, in the 1:3 ratio, 100g of pomelo peels were combined with 300 ml of n-Hexane for an extraction time of 12 hours. These experiments aimed to identify the optimal ratio yielding the highest extraction efficiency for the waste pomelo peels.

In the final optimization phase, the effectiveness of two pomelo peels, fresh grind and dry grind, was compared with n-hexane as the solvent. This comparison aimed to assess whether the type of pomelo peel impacted extraction efficiency. For fresh-grind and dry-grind pomelo peels, 100g of raw materials were utilized, with 250ml of n-Hexane employed, resulting in a ratio of 1:2.5 of pomelo peels to solvent. These experiments provided crucial data to evaluate the influence of pomelo peel type on the overall extraction performance.

3 RESULTS AND DISCUSSION

3.1 Selection of the Type of Waste Pomelo Peels

The choice of waste pomelo peel type was crucial for maximizing yield efficiency under the lab-scale water distillation apparatus. Figure 1 depicted the yield variations among different types, with fresh-grind pomelo peels demonstrating significantly higher efficiency. As a result, fresh-grind pomelo peels were chosen for subsequent experiments.

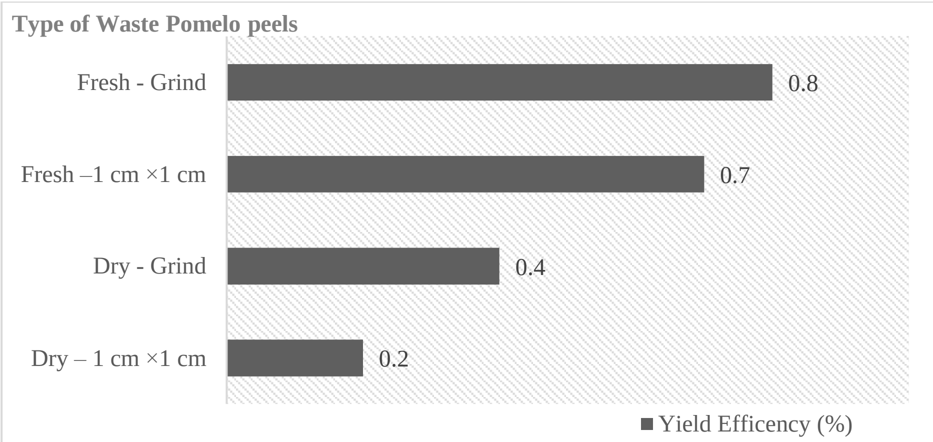

Figure 1. Selection of the type of waste pomelo peels

The superior yield efficiency of fresh-grind waste pomelo peels can be attributed to increased surface area achieved through grinding. This factor enhances contact between the solvent and essential oil-containing components within the peels, facilitating a more efficient extraction process. Additionally, the freshness of the pomelo peels contributes to higher yield efficiency, as fresh peels may contain higher concentrations of essential oils. The volatile nature of essential oils is better preserved in fresh materials, resulting in a more effective extraction.

3.2 Selection of the Best Extraction Method

Three extraction methods were compared: two using water distillation and one using soxhlet extraction. The soxhlet method showed the highest efficiency, leading to its selection for further optimization. This method's success is attributed to its continuous extraction process, allowing for prolonged contact between the solvent and pomelo peels. In contrast, the industrial-scale water distillation unit displayed lower efficiency, likely due to operational challenges such as uneven heat distribution and shorter extraction times. Optimizing and maintaining the equipment is crucial for improving its efficiency.

3.3 Process Optimization

In the initial phase of the process optimization, the yield efficiency variation for each solvent was analyzed, as depicted in Figure 3. The results indicated that n-hexane exhibited higher yield efficiency compared to other solvents.

The superior yield efficiency observed with n-hexane can be attributed to its favourable solvent properties. N-hexane possesses a suitable balance of volatility, polarity, and chemical compatibility, making it an effective extraction solvent for the essential oils present in waste pomelo peels. The specific chemical characteristics of n-hexane enable it to dissolve and extract the desired compounds efficiently, resulting in a higher yield than other solvents in experimental conditions.

Therefore, n-hexane was chosen as the best solvent for further experiments. All solvents were successfully recovered post-extraction, as shown in Table 1. This solvent recovery is vital for sustainability and cost-effectiveness, reducing the need for new solvent purchases and minimizing environmental impact. Recovery efficiency varied between 50% and 70% due to solvent nature and extraction conditions. For instance, n-hexane showed a 66.7% recovery rate, likely due to its compatibility with pomelo peels. The lab-scale water distillation setup used for recovery could have influenced efficiency. Additionally, solvent recycling promotes environmental safety, aligning with sustainable practices. Overall, solvent recovery highlights the commitment to economic and eco-friendly extraction processes.

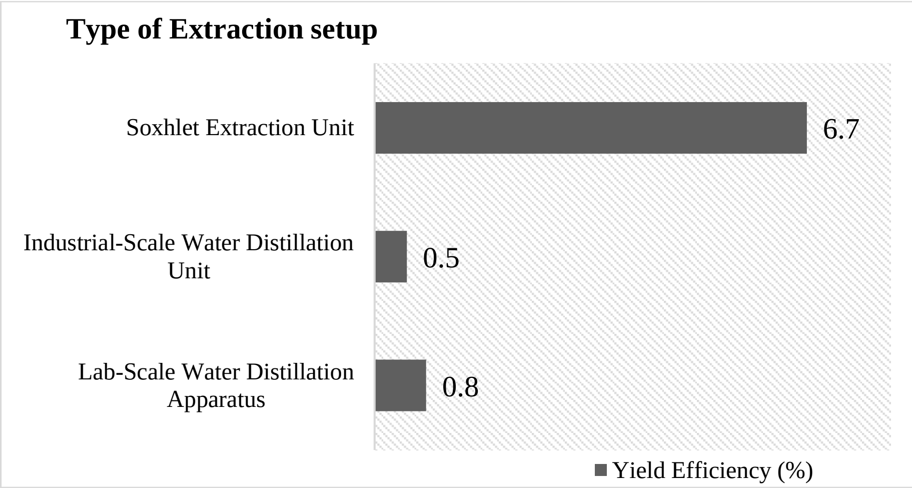

Figure 2. Selection of the best extraction method

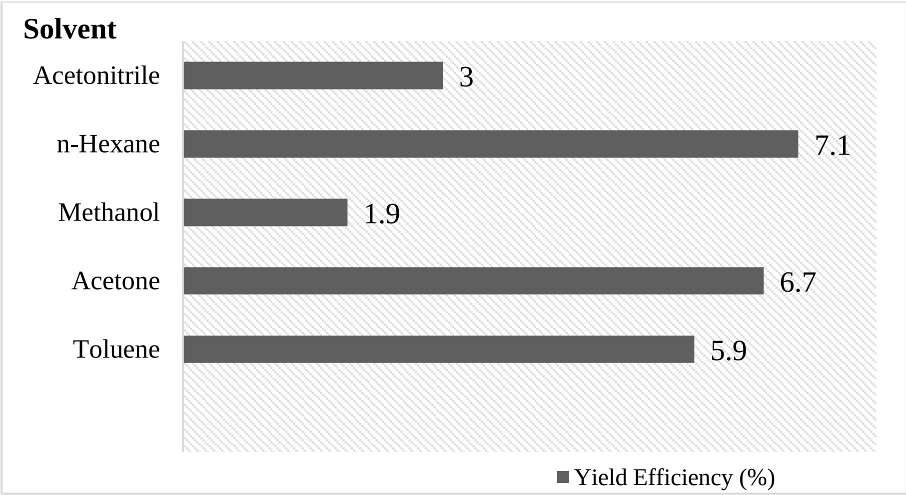

Figure 3. Selection of the most suitable type of solvent

The yield variation for different waste pomelo peels to n-hexane ratios was depicted in Figure 4 while exploring optimal ratios. The analysis concluded that the most effective ratio was 1:2.5, indicating that this proportion yielded the highest yield efficiency. To produce 7.7 ml of essential oil, 100 g of waste pomelo peels were processed using 250 ml of n-hexane. These variations were attributed to the intricate balance between solvent volume and waste pomelo peel quantity. In this case, the optimal ratio was 1:2.5, yielding slightly higher than other tested ratios.

It's worth noting that factors like the solubility of essential oils in the solvent, saturation point, and extraction time influenced yield efficiency. The slight differences in yield across ratios emphasized the process's sensitivity to these variables, highlighting the need for precise control and optimization.

Table 1. Details of solvent usage and recovery

Solvent	**Volume of solvent usage (ml)**	**Volume of recovered solvent (ml)**	**Percentage of recovered solvent (%)**
Toluene	300	168	56
Acetone	300	170	56.7
Methanol	300	195	65
n-Hexane	300	200	66.7
Acetonitrile	300	150	50

All n-Hexane used was successfully recovered, promoting sustainable practices. Table 2 shows the volumes of recovered n-Hexane for each experimental condition, indicating its potential for reuse in future extractions. The consistent decrease in recovered volume suggests that ground waste pomelo peels absorbed a fixed amount of n-Hexane during extraction. This sustainable approach improves economic efficiency and reduces solvent waste, aligning with environmental considerations. The recovery and reuse of all n-Hexane highlight the possibility of developing eco-friendly and cost-effective extraction protocols for waste pomelo peel essential oil.

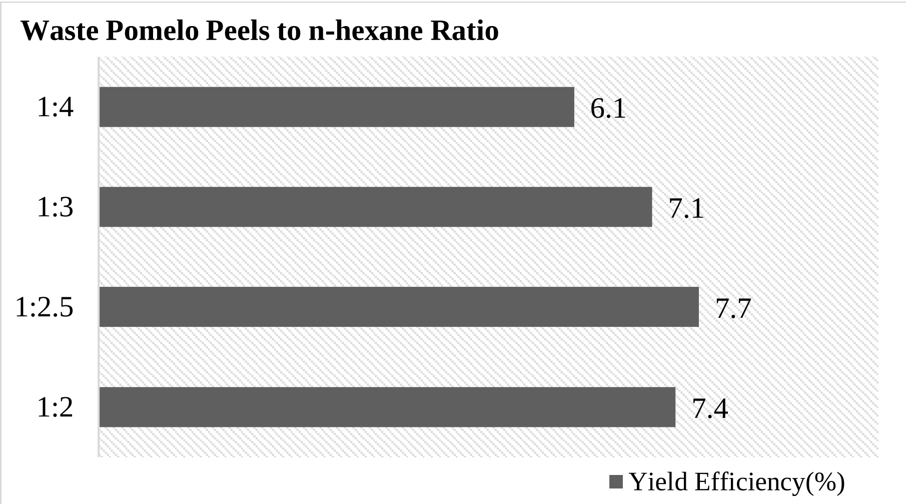

Figure 4. Selection of the best waste pomelo peels to n-hexane ratio

In the subsequent process optimization phase to enhance yield efficiency, the focus shifted towards selecting the most suitable waste pomelo peels. Previous experiments were conducted using water distillation results, and the results in the soxhlet extraction are presented in Figure 5. The analysis revealed that the fresh-grind variety is the best type of waste pomelo peels for both extraction methods.

The higher yield efficiency observed for fresh-grind waste pomelo peels in the case of the Soxhlet extraction method can be attributed to several factors. Firstly, the Soxhlet extraction method allows for prolonged and continuous extraction, ensuring more efficient raw material utilization. The constant circulation of the solvent in the Soxhlet apparatus facilitates the thorough extraction of essential oils from the fresh-grind waste pomelo peels.

Table 2. Overview of recovered n-Hexane volumes

Volume of n-Hexane (ml)	Recovered n-Hexane (ml)	Wasted volume of n-hexane (ml)
200	100	100
250	150	100
300	200	100
400	300	100

The Soxhlet extraction method involves a reflux process, where the solvent repeatedly cycles through the solid material. This cycling action enhances the contact between the solvent and the fresh-grind pomelo peels, promoting a more complete extraction of essential oils. The prolonged extraction time and thorough solvent circulation likely contribute to the higher yield efficiency observed in the Soxhlet extraction method, mainly when applied to fresh-grind waste pomelo peels.

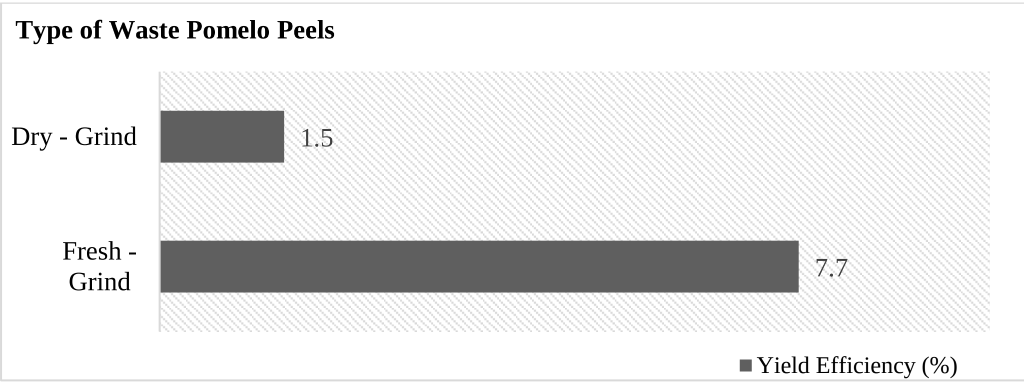

Figure 5. Selection of the best type of waste pomelo peels

The essential oil extracted from pomelo peels via Soxhlet extraction was analyzed using GC-MS to determine its chemical composition. Various compounds were identified, with limonene found to be the most abundant. Other notable compounds included 2,6-Dimethyl-1,3,5,7-octatetraene, 2-Cyclohexen-1-one, 2-methyl-5-, and Mentha-1,4,8-triene. Smaller amounts of alpha-pinene, and linalool oxide cis were also detected. Importantly, no n-hexane compounds were detected in the final oil sample, indicating successful recovery during the extraction process. The high concentration of limonene aligned with findings from previous studies on citrus essential oils, underscoring its significance in the overall composition. These compounds collectively contributed to the distinct aroma and potential therapeutic properties of the essential oil extracted from pomelo peels.

3.4 Energy and Production Cost Analysis

The study analyzed the energy consumption and production costs of extracting essential oils from waste pomelo peels using various methods. It examined energy costs, transportation expenses for waste peels, and the procurement costs of extraction solvents. In the Energy and Production Cost Analysis, the energy consumption for all setups was calculated in kilowatt-hours (kWh) using an energy meter. The TATA Dimo Batta, with a capacity of up to 750,000 g (750 kg), is priced at 16,000 LKR. Additionally, a 200 L barrel of n-hexane costs 70,000 LKR. The cost of n-hexane included the expenses for waste n-hexane since all n-hexane used in the extraction processes was recovered for reuse. The findings indicated that industrial-scale water distillation units boasted the lowest production costs compared to soxhlet extraction and lab-scale water distillation setups.

3.5 Economic Viability of Commercial Pomelo Cultivation in Sri Lanka

Based on the information provided by the Department of Agriculture (2024) and the assumptions made:

- One hectare (ha) of pomelo trees in Sri Lanka typically consists of 500 trees.
- Each tree yields approximately 60 fruits per year.
- The oil content extracted via the soxhlet extraction method is around 5%.
- One pomelo fruit peel weighs 250g, resulting in 12.5 ml of oil per fruit.

The soxhlet extraction apparatus was utilized to calculate the annual production cost for 375 litres per hectare. Using this method, the total production cost for 1 L of essential oil was 68.37 USD. The total production cost amounted to 25,638.75 USD, extrapolating this to 375 L considering an annual income of 150,000 USD, the profit per year was computed by subtracting the production cost from the total revenue, resulting in approximately 124,361.25 USD. The profit percentage was then calculated to be approximately 82.9%. Hence, the annual profit from extracting 375 litres of essential oil per hectare using the soxhlet extraction apparatus was estimated to be around 124,361.25 USD, with a profit margin of approximately 82.9%.

3.6 Life Cycle Analysis

The Life Cycle Assessment (LCA) using Mobius software analyzed the soxhlet extraction and industrial-scale water distillation methods. Figures 6 and 7 show each method's carbon dioxide (CO_2) emissions. Surprisingly, the LCA found that soxhlet extraction had a much more significant CO_2 impact than industrial-scale water distillation. This result means the soxhlet method has a larger environmental footprint because it requires more energy and solvents.

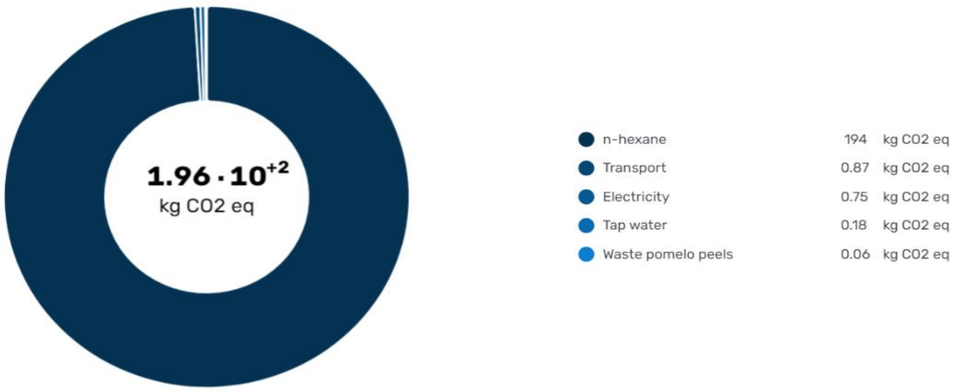

Figure 6. Impact per item of Soxhlet extraction using waste pomelo peels on climate change

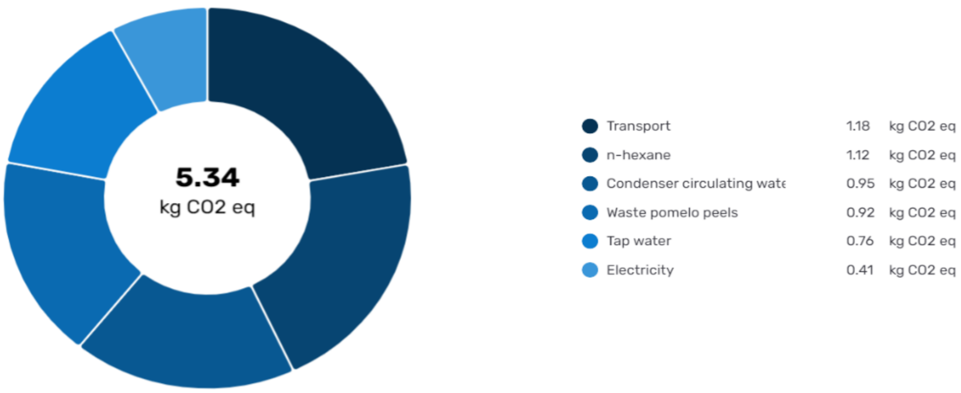

Figure 5. Impact per item of water distillation using waste pomelo peels on climate change

4 CONCLUSION

In conclusion, this research explored optimizing essential oil extraction from waste pomelo peels using water distillation and soxhlet extraction. Through various experiments and optimizations, it was found that the soxhlet extraction method yielded higher efficiency compared to water distillation. This method's continuous extraction allowed for prolonged contact between the solvent and pomelo peels, resulting in better extraction efficiency.

Furthermore, the study investigated the economic viability of essential oil production from pomelo peels, mainly focusing on the soxhlet extraction method. The analysis showed promising profit margins, indicating the potential for commercial cultivation of pomelo trees for essential oil extraction in Sri Lanka.

However, it is essential to consider the environmental impacts. The Life Cycle Assessment (LCA) revealed that soxhlet extraction has a larger carbon footprint than industrial-scale water distillation due to its higher energy and solvent requirements.

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